TRANSPORTATION RESEARCH RECORD 646

Transportation Ride Quality

TRANSPORTATION RESEARCH BOARD

COMMISSION ON SOCIOTECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1977

Transportation Research Record 646
Price $3.00
Edited for TRB by Frances R. Zwanzig

subject areas
03 rail transport
04 air transport
52 road user characteristics
84 urban transportation systems

Transportation Research Board publications are available by ordering directly from the board. They may also be obtained on a regular basis through organizational or individual supporting membership in the board; members or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

Notice
The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The views expressed in this report are those of the authors and do not necessarily reflect the view of the committee, the Transportation Research Board, the National Academy of Sciences, or the sponsors of the project.

Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Transportation ride quality.

(Transportation research record; 646)
Includes bibliographical references.
1. Vehicles–Riding qualities–Addresses, essays, lectures.
2. Vehicles–Vibration–Addresses, essays, lectures. 3. Vehicles–Heating and ventilation–Addresses, essays, lectures. I. Title.
II. Series.
TE7.H5 no. 646 [TA1155] 380.5'08s [629.04]
ISBN 0-309-02675-X 78-16961

Sponsorship of the Papers in This Transportation Research Record

GROUP 3–OPERATION AND MAINTENANCE OF TRANSPORTATION FACILITIES
Adolf D. May, University of California, Berkeley, chairman

Task Force on Ride Quality
D. William Conner, NASA Langley Research Center, chairman
A. Robert Kuhlthau, University of Virginia, secretary
Stanley H. Brumaghim, Karl H. Dunn, J. C. Guignard, Anthony J. Healey, J. Karl Hedrick, Stanley E. Hindman, Slade F. Hulbert, Richard L. Scharr, Ronald G. Schlegel, E. Donald Sussman

Adrian G. Clary, Transportation Research Board staff

The organizational units and officers and members are as of December 31, 1976.

Contents

Comparison of Passenger-Comfort Models in Buses, Trains, and Airplanes

I. D. Jacobson and R. W. Barber, Department of Engineering Science and Systems, University of Virginia
R. D. Pepler and L. L. Vallerie, Dunlap and Associates, Inc., Darien, Connecticut

Recent controlled experiments concerning passenger ride comfort in intracity buses and intercity trains are reported and compared with past airplane ride-comfort studies. The primary method of analysis is linear regression of environmental and motion factors versus passengers' perceived ride comfort. The regression coefficients so obtained are compared among the three transportation modes for similarities. Transverse acceleration, vertical acceleration, and noise appear to be the dominant determinants of ride comfort in airplanes, roll is the major determinant of ride comfort in buses, and noise and roll are dominant in trains. Despite the differences in the dominant variables, the estimated regression coefficients for the different motions and noise are similar across all three modes. This suggests the possibility of a single general model incorporating all motions and environmental factors.

The modeling of passenger ride quality in transportation systems has received much attention in the past several years. Most of the work can be separated into three general areas. The first of these is laboratory studies that deal mainly with reactions to motion stimuli; the second is field studies that use captive subjects to determine reactions to the general environment (not exclusively motion); and the last is field studies that use fare-paying passengers. These studies have been reviewed elsewhere (1, 2, 3, 4).

Basically, past ride-quality studies have determined the relations between subjective comfort response and motion or multiple stimuli (e.g., motion, noise, and temperature). These models take the form of either equi-sensation-type contours (5) or regression models (6, 7, 8), in which comfort is the dependent variable and the various environmental parameters (such as vertical acceleration, transverse acceleration, roll rate, temperature, and pressure) are the independent variables.

This paper compares ride-quality models developed at the University of Virginia with field studies of both captive and fare-paying passengers on buses, trains, and airplanes. The results for the airplane models are well documented (7, 8, 9, 10, 11, 12) and will not be repeated. Generally, however, those studies were conducted in a manner similar to the bus and train studies described here.

DESCRIPTION OF BUS AND TRAIN EXPERIMENTS

A pair of experiments were performed to develop data on the effects of the environment of a vehicle on passenger comfort in intracity buses and intercity trains. These experiments were designed to simultaneously collect information on the vehicle's environment and the passenger's comfort ratings in that environment. The data on the vehicle's motion were collected by using the University of Virginia's portable environmental measurement system. This equipment consists of a portable measurement box and a standard tape recorder. It is capable of measuring and recording three linear accelerations, three angular rates, temperature, pressure, and noise. Analog measurements are FM-multiplexed on the tape recorder for later retrieval and reduction by analog and digital computers. For the present study, the data so collected were analyzed by using root-mean-square (RMS) values, where deviations are measured against the mean value of the data. This gave a set of RMS values (mean biased out), with the linear accelerations in *g*s and the angular velocities in degrees per second. The test period was subdivided into approximately 1-min segments, each with a somewhat different environmental stimuli. The subjects were asked to rate the comfort of the ride in each of the segments on a scale of 1 to 7, with the following scale characterization:

Comfort Level	Scale
Very comfortable	1
Comfortable	2
Somewhat comfortable	3
Neutral	4
Somewhat uncomfortable	5
Uncomfortable	6
Very uncomfortable	7

The subjects were not coached as to the motion levels that define these comfort levels; all responses were subjective, with the subject himself or herself defining what was comfortable or uncomfortable.

The bus experiment was designed so that the subjects would ride on two different buses, one with a good suspension and one with a poor suspension. A route in the Hartford, Connecticut, area was selected for the experiment such that many different levels of motion would be experienced by the subjects.

The train experiment used four different passenger coaches on the New York to Boston line in the Stamford to New London area. Because it was impossible to control the route in this case, data were gathered at periodic intervals (every 6 min). Again, different coaches were used with different suspension characteristics. The table below shows the experimental design for both the bus and train experiments.

Subject Group	Vehicle Suspension Trial 1	Vehicle Suspension Trial 2
A	Poor	Good
B	Good	Poor

In these experiments, the subject groups were matched for age (young, middle, or older), sex, and frequency of vehicle use (seldom or frequent), and each trial, in which the data were collected over fifteen to twenty 1-min trip segments, was conducted over the same preselected test route.

Table 1. Statistical comparison of bus, train, and airplane motion.

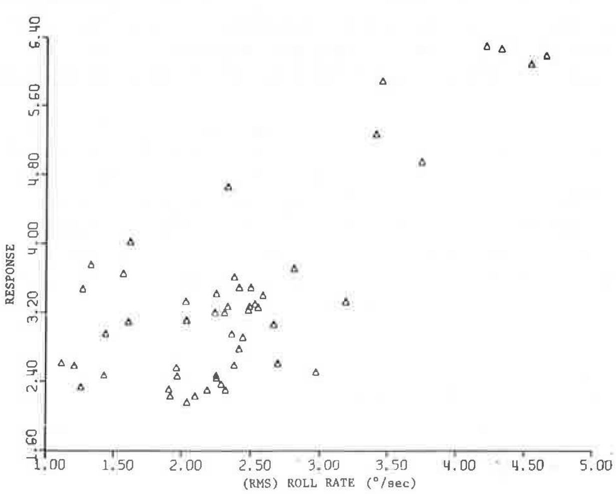
Information	Bus	Train	Commercial Airplane
Subjective response			
Mean	3.4	2.9	3.2
SD	1.1	0.7	0.9
Range	2.2 to 6.3	1.7 to 4.8	2 to 6
Roll rate, °/s			
Mean	2.4	1.4	1.0
SD	0.8	0.3	0.7
Range	1.1 to 4.6	0.9 to 2.6	0.11 to 3.6
Pitch rate, °/s			
Mean	2.1	0.51	0.3
SD	0.5	0.10	0.25
Range	1.2 to 3.4	0.76 to 1.1	0.05 to 2.2
Yaw rate, °/s			
Mean	2.1	1.3	0.26
SD	0.6	0.3	0.37
Range	1.1 to 3.5	0.8 to 2.7	0.009 to 3.6
Longitudinal acceleration, *g*			
Mean	0.044	0.012	0.014
SD	0.015	0.004	0.012
Range	0.017 to 0.073	0.007 to 0.022	0.001 to 0.076
Transverse acceleration, *g*			
Mean	0.075	0.029	0.014
SD	0.028	0.010	0.012
Range	0.031 to 0.134	0.009 to 0.064	0.001 to 0.080
Vertical acceleration, *g*			
Mean	0.082	0.030	0.044
SD	0.027	0.007	0.031
Range	0.036 to 0.152	0.018 to 0.049	0.008 to 0.19
Noise, dB(A)			
Mean	75.8	70.4	87
SD	2.6	4.4	2.7
Range	70 to 83	62 to 82	81 to 94
Temperature, °C			
Mean	22.2	23.3	20.0
SD	1.8	3.6	6.0
Range	18.3 to 23.9	20.0 to 27.8	12.2 to 30.56

Note: °C = (°F - 32)/1.8.

Table 2. Correlation coefficients for bus data.

Item	Subject Response	Roll	Pitch	Yaw	Longitudinal Acceleration	Transverse Acceleration	Vertical Acceleration	Noise	Temperature
Subject response	1.00	–	–	–	–	–	–	–	–
Rôll	0.76	1.00	–	–	–	–	–	–	–
Pitch	0.22	0.57	1.00	–	–	–	–	–	–
Yaw	0.05	0.39	0.63	1.00	–	–	–	–	–
Longitudinal acceleration	0.48	0.57	0.50	0.48	1.00	–	–	–	–
Transverse acceleration	0.28	0.59	0.80	0.77	0.61	1.00	–	–	–
Vertical acceleration	0.57	0.71	0.68	0.60	0.62	0.77	1.00	–	–
Noise	0.07	0.28	0.47	0.52	0.25	0.56	0.51	1.00	–
Temperature	-0.08	-0.29	-0.41	-0.35	-0.29	-0.43	-0.29	-0.08	1.00

Figure 1. Mean subject response versus (RMS) roll rate for bus experiment.



RESULTS OF BUS AND TRAIN EXPERIMENTS

Bus

In the bus experiment, environmental data and the responses of 30 subjects were collected for each of 52 road segments. Within each segment, the variation among the individual responses had a standard deviation (SD) of approximately 1.3. The measure used in the following discussion is the mean of the 30 subjects' responses for each segment.

Table 1 summarizes the statistical information gathered in the bus, train, and airplane studies. The data display a relatively wide spread in all of the motion variables. The coefficient of variation for all motion variables exceeds 25 percent; only in the noise variable is the spread much lower, with a coefficient of variation of 3 percent [this, of course, is misleading because the dB(A) measure is logarithmic rather than linear]. The data on pressure are not given because of the insignificant variation in this variable.

Table 2 gives the Pearson correlation coefficients of the mean responses, motion variables, noise, and temperature. The relations among the responses of the subjects and the individual motions can be seen more clearly in Figure 1, which relates the mean response (on the vertical axis) and the mean roll rate (on the horizontal axis) for the collected data.

Because of the high colinearity among the independent motion variables, stepwise linear regression was used to examine their relationship with the dependent variable (comfort). [The stepwise regression technique has been used in similar studies (7) with satisfactory results.]

The results of the regression analysis can be expressed by a comfort-model equation having the following form:

$$C = A + B\omega_R \qquad (1)$$

where

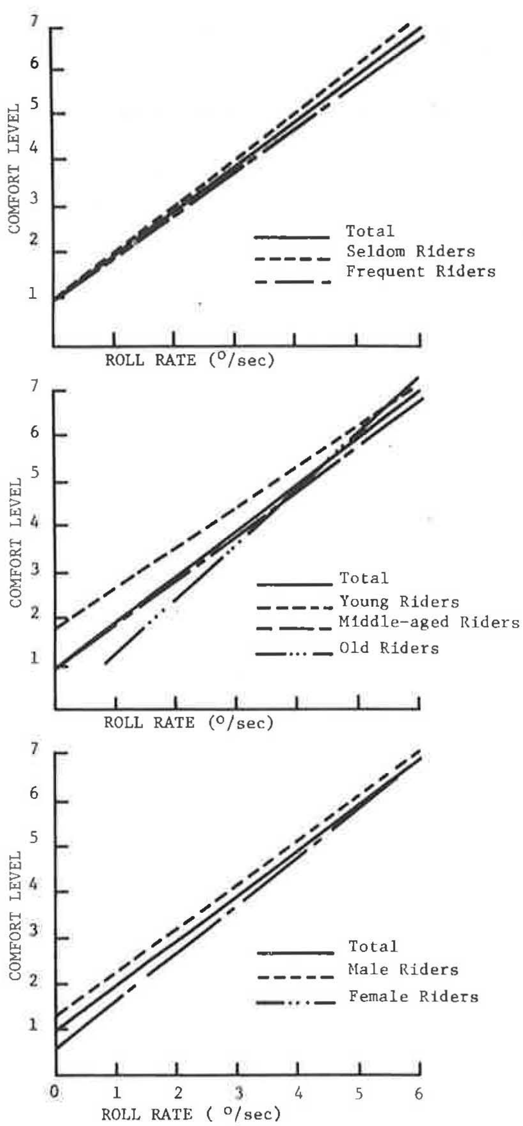
C = comfort rating,
A and B = coefficients, and
ω_R = roll rate (°/s).

Table 3. Comfort models using bus experimental data.

Category of Subjects	A Value	A SE[a]	B Value	B SE[a]	R^2	Level of Significance
All	0.87	0.32	1.05	0.13	0.58	<0.001
Seldom riders	0.79	0.31	1.12	0.12	0.62	<0.001
Frequent riders	0.93	0.33	0.97	0.13	0.53	<0.001
Ages 16 to 24	1.71	0.31	0.91	0.12	0.53	<0.001
Ages 25 to 48	0.84	0.38	1.01	0.15	0.47	<0.001
Ages ≤49	-0.22	0.37	1.28	0.14	0.61	<0.001
Males	1.25	0.31	0.99	0.12	0.56	<0.001
Females	0.47	0.35	1.09	0.14	0.56	<0.001

[a] SE = standard error.

Figure 2. Comfort versus roll rate by category of subject.



The coefficients, R^2 statistics, and levels of significance for all categories of riders are given in Table 3. RMS roll rate is the dominant variable in all cases. It is noteworthy that the R^2 statistic is greater than 0.50 except for the ages 25 to 48 category and that the level of significance in all equations is better than 0.001.

Although the stepwise regression enters yaw, pitch, and vertical acceleration into the equation at the 0.05 level of significance, these variables are not included in the model. The coefficients of these variables are not all positive, a counter-intuitive result. For example, the second variable to enter the equation (for all subjects) is yaw, resulting in the following equation:

$$C = A + B\omega_R - D\omega_Y \quad (R^2 = 0.65) \qquad (2)$$

where D = coefficient and ω_Y = yaw rate (°/s). The coefficients and standard errors (SEs) for this equation are given below.

Coefficient	Value	SE
A	1.68	0.39
B	1.20	0.13
D	0.55	0.18

It is not realistic that increased yaw in a vehicle's motion will increase the comfort of the passenger for the range of frequencies encountered. These additional terms are therefore not used because they do not reflect a theoretically sound basis for a comfort model.

Graphic representations of the individual regression equations, by category, are shown in Figure 2. Both the constants and the slope coefficients are of interest. The three categories of subjects will be considered separately. First, seldom riders have a lower intercept coefficient, but a higher slope coefficient than do frequent riders; however, these results are not statistically significant because of the relative magnitudes of the standard errors and should only be considered as trends. When subdivided by age, young riders are generally less satisfied with the bus ride, as evidenced by the large intercept coefficient, but are more tolerant of the roll motion; older riders are generally more satisfied with the ride, but are more sensitive to the rolling motion. In the male and female categories, the intercepts are significantly different, but the slopes are not. Males tend to be generally more intolerant of the ride than are females, but their responses to the vehicle motion are approximately the same.

Train

In the train experiment, the responses of 30 subjects were collected on each of 79 track segments. As in the bus analysis, the dependent variable is the mean response of these 30 subjects.

The train data are summarized in Tables 1 and 4. Table 1 gives a statistical summary of the environmental data, including the mean, standard deviation, and range of each variable for the 79 segments. The motion data collected in the train experiment had noticeably less variation than that collected in the bus experiment. For example, the train data have coefficients of variation of 20 and 11 percent for roll and pitch respectively with others in the range of 23 to 35 percent. Table 4 gives the partial correlation coefficients for the train data. The noise level has the highest correlation with the subject responses, and the roll and transverse acceleration have partial correlations of 0.44 and 0.34 respectively.

The stepwise regression approach used in analyzing the train data produced regression equations of the following form:

$$C = A + E\,dB(A) + B\omega_R \tag{3}$$

The coefficients, R^2 statistics, and levels of significance of these equations for all categories of riders are given in Table 5. In these models, the noise and roll variables together explain 52 percent of the total variance in the subjects' responses. The next variable to enter is longitudinal acceleration, which increases the R^2 statistic from 0.52 to 0.54. This small increase does not warrant inclusion in the model, and this variable is not entered.

AIRCRAFT DATA

Data were taken on flights of four different commuter airlines, each flying different aircraft with flight times of 15 to 60 min. The aircraft involved were all small (15 to 30 passengers) and short haul [<800 km (<500 miles)]. In addition, flights onboard an in-flight aircraft simulator were conducted using special subjects to obtain responses to motion environments not experienced in present-day commercial aircraft. These flights are described elsewhere (13). Stepwise linear regression analysis yielded the following models for comfort.

For the commercial flights, the data are summarized in Table 1, and the correlation coefficients are given in Table 6. The motion terms with the highest correlation with comfort are vertical and transverse accelerations and roll. Noise is a smaller contributor; however, it is included here for completeness. Because the comfort equation is nonlinear, two equations were fitted to the airplane data depending on the relative magnitudes of the transverse and vertical accelerations (8). These equations are given below:

$$C = 2.1 + 18.9a_V + 12.1a_T + 0.19[dB(A) - 85.5] \quad (a_V \geq 1.6a_T) \tag{4a}$$

$$C = 2.1 + 1.6a_V + 39.8a_T + 0.19[dB(A) - 85.5] \quad (a_V < 1.6a_T) \tag{4b}$$

where a_V and a_T are vertical and transverse accelerations respectively. For these two equations, $R^2 = 0.41$, and the sample sizes are 2000 and 1680 respectively.

Although no sex-specific or age-specific models have been generated, it has been observed (9, 10) that women are less sensitive to motions than are men.

In the airplane-simulator flights, it was possible to generate motions that allowed the investigation of one variable at a time. In this paper, only the response to roll rate is presented to allow a comparison with ground modes (13):

$$C = 1.34 + 0.76\omega_R \tag{5}$$

where the dominant frequency for the roll motion is 1 Hz. This is chosen to conform with the lowest dominant frequencies of the ground modes. No high-frequency roll-motion data are available because this type of motion does not occur in the air mode.

COMPARISON OF BUS, TRAIN, AND AIRPLANE MODELS

Before proceeding with comparisons of the models them-

Table 4. Correlation coefficients for train data.

Item	Subject Response	Roll	Pitch	Yaw	Longitudinal Acceleration	Transverse Acceleration	Vertical Acceleration	Noise	Temperature
Subject response	1.00	—	—	—	—	—	—	—	—
Roll	0.44	1.00	—	—	—	—	—	—	—
Pitch	0.31	-0.03	1.00	—	—	—	—	—	—
Yaw	0.20	0.62	-0.14	1.00	—	—	—	—	—
Longitudinal acceleration	0.43	0.06	0.18	0.05	1.00	—	—	—	—
Transverse acceleration	0.34	0.56	-0.18	0.77	0.07	1.00	—	—	—
Vertical acceleration	0.08	0.41	-0.38	0.18	-0.05	0.26	1.00	—	—
Noise	0.63	0.15	0.43	0.05	0.46	0.04	-0.13	1.00	—
Temperature	0.24	-0.04	-0.06	-0.03	0.21	-0.03	-0.22	0.27	1.00

Table 5. Comfort models using train experimental data.

Category of Subjects	A		E		B			
	Value	SE[a]	Value	SE[a]	Value	SE[a]	R^2	Level of Significance
All	-5.26	0.96	0.10	0.01	0.96	0.21	0.52	<0.001
Seldom riders	-4.26	0.96	0.08	0.01	1.05	0.22	0.48	<0.001
Frequent riders	-6.30	1.06	0.11	0.01	0.88	0.24	0.51	<0.001
Ages 16 to 25	-5.86	0.94	0.11	0.01	0.81	0.21	0.54	<0.001
Ages 25 to 48	-3.04	1.03	0.06	0.01	1.01	0.23	0.37	<0.001
Ages ≤49	-6.67	0.26	0.12	0.02	1.00	0.28	0.46	<0.001
Males	-6.20	1.09	0.11	0.02	0.86	0.24	0.50	<0.001
Females	-4.33	0.92	0.08	0.01	1.06	0.21	0.50	<0.001

[a] SE = standard error.

Table 6. Correlation coefficients for airplane data.

Item	Subject Response	Roll	Pitch	Yaw	Longitudinal Acceleration	Transverse Acceleration	Vertical Acceleration	Noise	Temperature
Subject response	1.00	—	—	—	—	—	—	—	—
Roll	0.71	1.00	—	—	—	—	—	—	—
Pitch	0.56	0.81	1.00	—	—	—	—	—	—
Yaw	0.30	0.50	0.66	1.00	—	—	—	—	—
Longitudinal acceleration	0.30	0.41	0.54	0.25	1.00	—	—	—	—
Transverse acceleration	0.68	0.86	0.78	0.57	0.40	1.00	—	—	—
Vertical acceleration	0.74	0.91	0.78	0.40	0.39	0.82	1.00	—	—
Noise	0.18	—	—	—	—	—	—	1.00	—
Temperature	-0.13	—	—	—	—	—	—	—	1.00

Figure 3. Normalized lateral-acceleration power spectra for bus, train, and airplane motion.

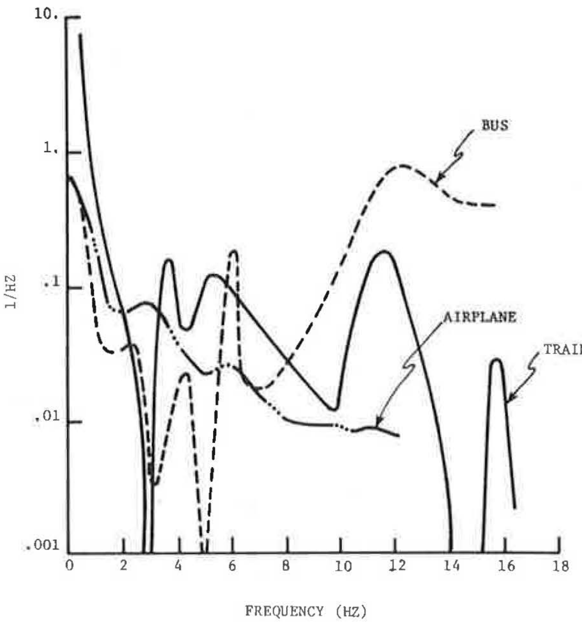
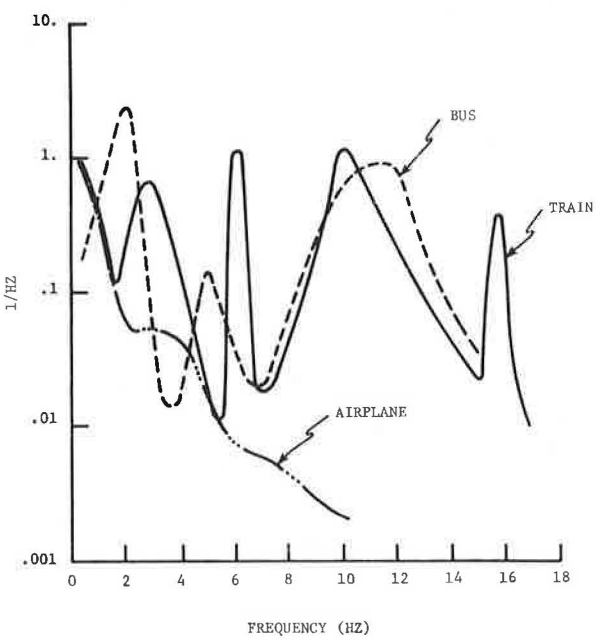


Figure 4. Normalized vertical-acceleration power spectra for bus, train, and airplane motion.



selves, it is important to note several differences in the data. First, the frequency distributions of the three modes are different (Figures 3, 4, and 5). The airplane motion is dominated by low-frequency components (i.e., <2 Hz) for roll rate and vertical and lateral acceleration, but the bus motion, and to a lesser extent the train motion, have more high-frequency components. A second difference is the range of motion encountered for the three modes. Table 1 indicates that there is less angular motion on the airplane than on the ground modes. In addition, there are significantly higher noise levels on board the aircraft. Of course, as in any regression analysis, caution should be used in applying the models to situations outside the range of the experimental data.

Figure 5. Normalized roll-rate power spectra for bus, train, and airplane motion.

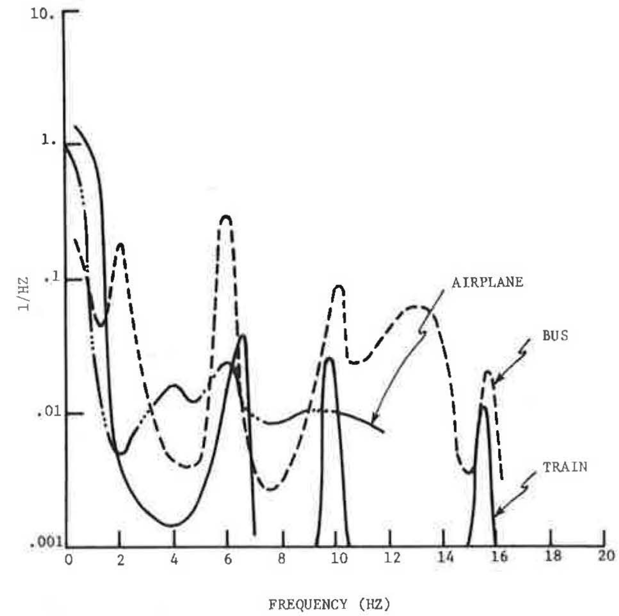


Table 7. Regression coefficients by mode and motion.

	Stimulus			
Vehicle Type	Roll	Vertical	Transverse	Noise
Bus	1.05 ± 0.13	16.6 ± 5.2[a]	—	—
Train	0.96 ± 0.21	—	28.6 ± 8.5[a]	0.10 ± 0.01
Airplane ($a_v \geq 1.6a_l$)	0.76[a]	18.9 ± 1.0	12.1 ± 0.2	0.19 ± 0.03[a]
Airplane ($a_v < 1.6a_l$)	—	1.6 ± 0.7	39.8 ± 8.6	0.19 ± 0.03

[a] Not an important variable for mode.

Although the models obtained are somewhat different in nature, they do have similarities. However, as regression models apply only within the limited range for which there are data, it is not surprising that different travel modes have different regression models. These differences suggest an examination of the influences of the environmental variables. In Table 7, four variables—roll rate, vertical acceleration, transverse acceleration, and noise—are compared. The three major models are summarized below:

1. Bus: $C = 0.87 + 1.05\omega_R$,
2. Train: $C = -5.27 + 0.96\omega_R + 0.10\text{dB(A)}$, and
3. Airplane: $C = 2.1 + 18.9a_v + 12.1a_T + 0.19\,[\text{dB(A)} - 85.5]$ for $A_v \geq 1.6a_T$ and $C = 2.1 + 1.6a_v + 39.8a_T + 0.19\,[\text{dB(A)} - 85.5]$ for $a_v < 1.6a_T$.

Within the statistical accuracies given (and remembering that some of the variables are secondary influences for a particular mode), the agreement is good. The roll coefficients are similar, with those for bus, train, and airplane all in the range of 0.76 to 1.05. The vertical coefficient for the bus data (16.6) lies between the coefficients for the two airplane models. This is a reasonable result, with the a_v/a_T ratio for the bus and train motion approximately unity (Table 1). Because this is close to the changeover point of a 1.6 ratio in the airplane equations, it is unclear which of the two airplane equations should be used in the comparison. There is a similar result in the transverse accelerations, where the train coefficient of 28.6 lies midway between the airplane coefficients of 12.1 and 39.8. The noise

Table 8. Roll-rate regression coefficients for bus and train data.

	Bus Data		Train Data	
Category of Subjects	Value	SE[a]	Value	SE[a]
All	1.05	0.13	0.96	0.21
Seldom riders	1.12	0.12	1.05	0.22
Frequent riders	0.97	0.13	0.88	0.24
Ages 16 to 24	0.91	0.12	0.81	0.21
Ages 25 to 48	1.01	0.15	1.01	0.23
Ages <49	1.28	0.14	1.00	0.28
Males	0.99	0.12	0.86	0.24
Females	1.09	0.14	1.06	0.21

[a] SE = standard error.

coefficients of 0.19 for airplane and 0.10 for trains are also in the same range, although statistically different (at a 0.05 level of significance). Table 8 gives additional information on the roll coefficients for bus and train subject subpopulations by age, sex, and frequency of ridership. Here again there is substantial agreement between the bus and train modes.

SUMMARY AND CONCLUSION

The data presented suggest that passenger sensitivity to the different vehicle motions are similar, regardless of the mode. Because of the dissimilarities in the dominant motions and in the frequency ranges encountered, conclusions beyond this must necessarily be guarded. Nonetheless, the results presented show a similarity in the marginal response to linear and angular motions that is reasonable from a physiological point of view and suggests the possibility of a general model of ride comfort that might be used on a variety of transportation modes. This general model might take the form of a multivariate model in which different motions and environmental factors are included or excluded depending on their relative dominance. This speculation is not unreasonable, given the similarity of the regression coefficients in the bus, train, and airplane ride-comfort models.

ACKNOWLEDGMENT

This work was sponsored in part by the Transportation Systems Center, U.S. Department of Transportation.

REFERENCES

1. A. R. Kuhlthau and I. D. Jacobson. Investigation of Traveler Acceptance Factors in Short-Haul Air Carrier Operations. Proc., Symposium on Vehicle Ride Quality, Langley Research Center, National Aeronautics and Space Administration, Hampton, Va., Technical Memorandum X-2620, Oct. 1972.
2. Ride-Quality Symposium and Workshop. Proc., National Aeronautics and Space Administration, Technical Memorandum X-3295; U.S. Department of Transportation, Rept. DOT-TSC-OST-75-40, Nov. 1975.
3. I. D. Jacobson. Criteria for Ride Quality—Motion. Short-Haul Air Transportation Program, Department of Engineering Science and Systems, Univ. of Virginia, Charlottesville, Memorandum Rept. 403202, Feb. 1972.
4. I. D. Jacobson. Environmental Criteria for Human Comfort—A Study of the Related Literature. Research Laboratories for the Engineering Sciences, Univ. of Virginia, Charlottesville, Rept. BE-4088-101-74; National Aeronautics and Space Administration, Contractor Rept. 132424, Feb. 1974.
5. T. K. Dempsey. A Model and Predictive Scale of Passenger Ride Discomfort. National Aeronautics and Space Administration, Technical Memorandum X-72623, Dec. 1974.
6. R. W. Stone, Jr. Simulator Studies and Psychophysical Ride Comfort Models. Proc., Ride-Quality Symposium and Workshop, Williamsburg, Va., National Aeronautics and Space Administration, Technical Memorandum X-3295; U.S. Department of Transportation, Rept. DOT-TSC-OST-75-40, Nov. 1975, pp. 615-664.
7. I. D. Jacobson and L. G. Richards. Ride-Quality Evaluation 2: Modeling of Airline Passenger Comfort. Ergonomics, Vol. 19, No. 1, 1976, pp. 1-10.
8. I. D. Jacobson. Construction and Verification of a Model of Passenger Response to STOL Aircraft Characteristics. Paper presented at SAE National Air Transportation Meeting, New York, Paper No. 760525, May 18 to 20, 1976.
9. L. G. Richards and I. D. Jacobson. Ride-Quality Evaluation 1: Questionnaire Studies of Airline Passenger Comfort. Ergonomics, Vol. 18, No. 2, March 1975, pp. 129-150.
10. L. G. Richards and I. D. Jacobson. Ride-Quality Assessment 3: Questionnaire Results of a Second Flight Program. Ergonomics, Vol. 20, No. 5, 1977, pp. 499-519.
11. I. D. Jacobson and A. N. Rudrapatna. The Effect of Interior Cabin Noise on Passenger Acceptance. Paper presented at the 1976 SAE Business Aircraft Meeting, Wichita, Kan., Paper No. 760466, April 6 to 8, 1976.
12. I. D. Jacobson, A. R. Kuhlthau, and L. G. Richards. Application of Ride-Quality Technology to Predict Ride Satisfaction for Commuter-Type Aircraft. Proc., Ride-Quality Symposium and Workshop, Williamsburg, Va., National Aeronautics and Space Administration, Technical Memorandum X-3295, U.S. Department of Transportation, Rept. DOT-TSC-OST-75-40, Nov. 1975, pp. 209-436.
13. E. W. McClurken, Jr. Acquisition of Passenger Ride-Quality Data Aboard the Total In-Flight Simulator (TIFS). Short-Haul Air Transportation Program, Technical Rept. 403220; National Aeronautics and Space Administration, Contractor Rept. 145957, Oct. 1975.

Assessment of Ride Quality of AIRTRANS System

A. J. Healey, Mechanical Engineering Department, University of Texas, Austin

The acquisition and analysis of ride-vibration data for the AIRTRANS automated-guideway-transit system at the Dallas-Fort Worth Regional Airport are discussed. The ride vibrations are measured as translational components of the vehicle floorboard accelerations in the three principal directions. The total record for a complete loop around the network was subdivided into sections of straight, gently curved, and sharply curved zones, and ensemble-averaged spectra for each type of zone were compared. The spectral-response characteristics between straight and gently curved zones are not very different, but the sharp turns increase the frequency, particularly in the 10 to 30-Hz range. The low-frequency behavior gives a multipeaked spectrum arising from the body and wheel modes as modified by kinematic resonances at frequencies corresponding to travel wavelengths that are multiples of the steering and main wheel bases. The ride quality was compared to a recent International Organization for Standardization standard, to a comfort criterion based on passenger satisfaction as found in small aircraft, and to ride ratings in a sedan automobile. All three predicted adequate ride satisfaction; the second method showed a 70 percent satisfaction level 94 percent of the time.

The ride quality of ground transportation systems is of current interest. While there is a good deal of knowledge about conventional systems using automotive, air, and rail vehicles, there is very little information about automated-guideway-transit systems. A recent example of such a system for group rapid-transit purposes is the AIRTRANS system at the Dallas-Fort Worth Regional Airport.

The AIRTRANS system consists of a network of U-shaped guideways, having both elevated and ground-level sections, inside which rubber-tired vehicles ride. The vehicle design is based on a modified truck chassis; individual vehicles are automatically controlled from a central computer for speed and location within the network. The vehicles have a passive steering system in which steering direction is given by rubber guide wheels that run on the guideway sidewall. There is provision for steering through bends and switches, including both merges and diverges. Each vehicle can accommodate up to 60 passengers. The system links approximately 14 stations with the Airport Marina Hotel and the north and south parking areas.

The route taken by a vehicle is controlled by the central computer control system, which gives signals to merge and diverge and switches rails appropriately, and the passive steering system, which guides the vehicle correctly through each switch point. Constant communication to and from the vehicle is maintained through signals transmitted through the signal rail; three-phase power is provided as the main driving source. A modified block control scheme is used. Each vehicle has a nominal route to take that depends on whether it is a passenger and employee or a utility vehicle. The nominal route will determine which station stops are made and which are bypassed.

Figure 1 shows the overall network schematic with its several interconnected loops. Figure 2 shows a typical AIRTRANS vehicle, which in its course around the network makes many turns, diverge and merge switches, and station stops.

From the point of view of ride quality, one of the important variables, known to be correlated with comfort (1), is that of vibration. For seated passengers, the vertical, longitudinal, and transverse components of low-frequency acceleration (0.1 to 40 Hz) are of direct concern (although the importance of the 20 to 40-Hz range has not been completely justified). In this work, the rotational degrees of motion have not been included. The sources of the vibration are primarily the on-board air compressor, excitation from unbalance and unevenness in the rolling stock, and roughness in the running surface and the sidewall steering surface. Because the AIRTRANS vehicle is laterally constrained with close tolerances, its vibration levels will be greater than are those of a typical sedan automobile that is relatively free to wander laterally.

This paper discusses the experimental techniques used to measure the floorboard acceleration levels found in an AIRTRANS vehicle and the data-reduction techniques used in their assessment. The results are given in terms of acceleration spectra, one-third-octave band analyses, and the variation of the root-mean-square (rms) acceleration levels around a typical transit loop. The idea of acceptability based on the percentage probability of achieving a given level of ride comfort is demonstrated.

EXPERIMENTAL METHOD

Instrumentation

The triaxial components of the linear acceleration were measured by using the battery-operated portable accelerometer set developed at Langley Research Center (2). This unit consists of three seismic-mass, strain-gauge type accelerometers, mounted in mutually perpendicular directions. The power supply is a 27-V source giving an output of approximately 5 V/g in each direction. Each axis is calibrated precisely before the field installation. The bandwidth of the accelerometer is from 0 to about 100 Hz.

A four-channel FM tape recorder was used to record the accelerometer output signals. The recorder is designed for a ±1.0-V range (±0.2 g) and has a 0 to 2000-Hz bandwidth, which is more than sufficient for this application. The first three channels were used to record the X, Y, and Z components of the acceleration, while the fourth channel was reserved for recording the vehicle speed. This latter signal was important because of the strong influence that vehicle speed has on vibration levels and was obtained by recording the output signal of the on-board tacho-pulser.

The instrumentation hardware was relatively simple because the method of data analysis was to record the raw data first and later process the records digitally.

Field Experiment

The accelerometer unit and tape recorder were installed in a single-car, passenger vehicle. The power for the tape recorder was supplied by a step-down transformer that picked up 440 V ac across two of the three phases that powered the vehicle and reduced it to 110-V 60-Hz power. An oscilloscope was used for signal monitoring to ensure that good quality data were obtained on the record. Generally, the 100-Hz bandwidth limitation

Figure 1. AIRTRANS guideway layout.

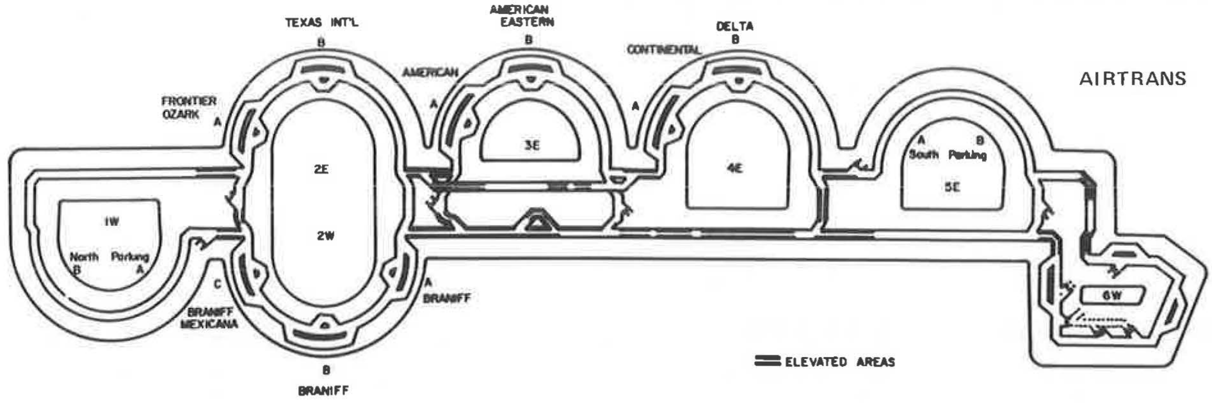


Figure 2. AIRTRANS vehicle.

of the triaxial accelerometer unit is adequate for eliminating unwanted high-frequency interference, and the signals obtained are relatively free from noise.

By careful selection and changing of designated routes, a special test route was designed that was a loop starting at the 5E south parking station, traveling through the 4E and 3E areas, crossing through the 3E bridge to the hotel station, and back along the long straight section to 5E; i.e., 5E to 4E to 3E to hotel to 5E. In this loop, the 3E bridge section has two sharp [46-m (150-ft) radius] curves and an assortment of gentle [242-m (800-ft) radius] curves in the semicircular terminal zones as well as a long straight section; thus, it encompasses all of the steering manuevers that the vehicles are required to accomplish.

Data Processing for Spectra and One-Third-Octave Band Analysis

The data processing technique used was based on digital methods and is described in detail elsewhere (4). The complete record for a loop illustrated that the nature of the vibration levels was highly variable because of vehicle-speed variations and effective-roughness input changes between straight and curved sections. There were only a few segments in which the results were approximately stationary. Because of this, segments of the total record were isolated corresponding to straight, gently curved, and sharply curved zones traveled at 0.25, 0.5, 0.75 and full speed. In the curved zones, the segments that exhibited nearly stationary results, i.e., a frequency resolution of 0.1 Hz, were of only 10-s duration.

Spectral densities were calculated by computing the discrete Fourier transform, extracting the mean value, and smoothing the resultant raw spectral estimates. The measure of statistical confidence in estimating the spectral-density values is the number of statistical degrees of freedom used in the averaging. In the results that follow, 6, 10, and 18 degrees of freedom were used respectively in the 0 to 1, 1 to 10, and above 10-Hz ranges for the individual section analyses. Better estimates of the spectra in specific zones [such as a 46-m (150-ft) radius turn] were later found by ensemble averaging each spectral-density value across sets of data taken from sections having the same characteristics, but obtained either at another location in the network or from the other run around the primary test loop.

The total mean-squared acceleration (σ^2) of a section is given by the sum of the spectral-density estimates [P(m)] divided by the record length (T). Thus

$$\sigma^2 = (1/T) \sum_{m=0}^{N/2} P(m) \tag{1}$$

To find the rms acceleration in band intervals of one-third octave, Equation 1 is applied over a frequency interval of $[\hat{f} - (B/2)]$ to $[\hat{f} + (B/2)]$, where $\hat{f}$ is the band-center frequency and B is the bandwidth. For a one-third-octave bandwidth, $B = 0.230\ 02\hat{f}$, and the rms acceleration in the band is

$$\sigma^2_{1/3}(\hat{f}) = (1/T) \sum_{\hat{f}-(B/2)}^{\hat{f}+(B/2)} P(f) \tag{2}$$

Because values of P(m) occur only at multiples of the digitizing frequency 1/T, where $(\hat{f} \pm B/2)$ is not an integer multiple of 1/T, allowance must be made to include the power that would otherwise be lost.

Probability Density and Cumulative Probability

The measures of the amplitude content, as opposed to those of the frequency content, of random vibrations are the probability density and the cumulative probability function of the signal. The probability density is the fraction of total samples lying within the band, i.e., $\bar{x} < x_i < (\bar{x} + dx)$, so that

$$p(\bar{x}) = [1/N(dx)] \sum_{i=0}^{N-1} x_i \quad [\bar{x} < x_i < (\bar{x} + dx)] \tag{3}$$

and the cumulative probability [cp ($\bar{x}$)] is a function of the acceleration level that gives the total fractional probability of having acceleration amplitudes less than some value $\bar{x}$.

$$cp(\bar{x}) = (1/N)\sum_{i=0}^{N-1} x_i \qquad (-\infty < x_i < \bar{x}) \tag{4}$$

Many processes for which enough samples are taken exhibit probability functions described by the Gaussian normal distribution and are thus described by a mean and a variance only.

In the examination of the experimental digitized records, probability functions have been obtained both for the probability of exceeding a given value of acceleration within a section and for the probability of exceeding a given rms level in any section for the total ride around the test loop.

RESULTS

By using the procedures described above and outlined in more detail by Healey and others (3), a series of test sections were isolated for detailed study. These sections were grouped in the general categories of

1. Full speed along the straight section between the hotel and 6W,
2. Full speed in the gently curved turns around the 4E and 3E terminals, and
3. Full speed in the sharply curved turns in the 3E bridge zone.

The effect of speed variation is complex and will be discussed in a later report.

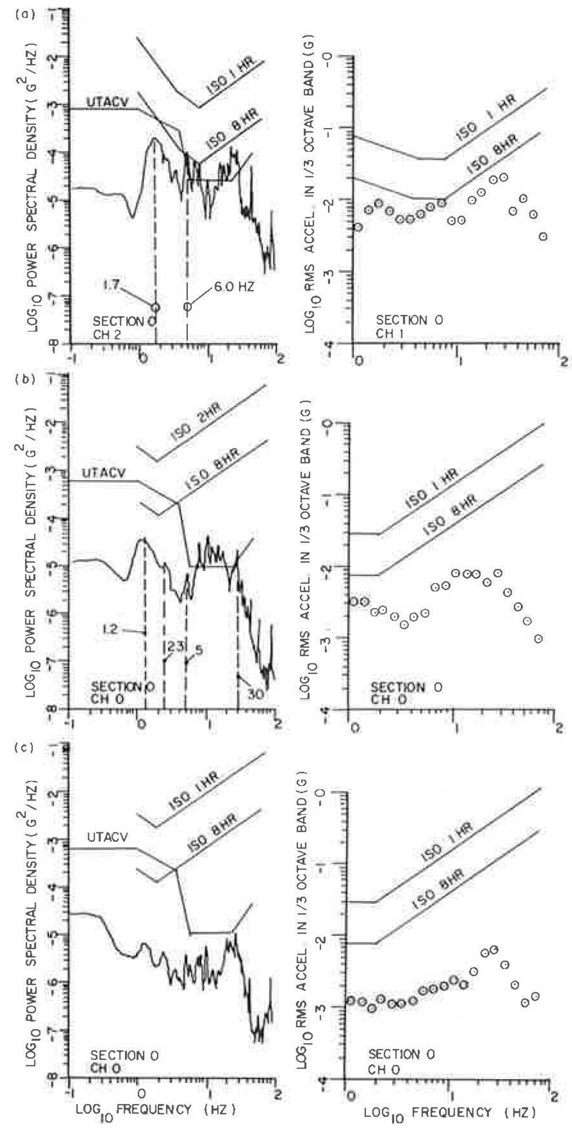
Spectra and One-Third-Octave Band Analysis

For the first category—travel along the back straight at full speed—five different sections of 10.4-s duration for each section were analyzed separately and the spectral-density values then ensemble averaged for each of the three acceleration components. The results for the ensemble-averaged spectra and the resulting one-third-octave band values are summarized in Figure 3. Figure 3 also shows lines corresponding to the 1 and 8-h reduced comfort guides (5) for comparison. For the spectral-density results, the reduced comfort guides have been converted into spectral-density levels on the basis of the one-third-octave bandwidth. Figures 4 and 5 show results similar to those of Figure 3; Figure 4 presents the results for full-speed travel around the gently curved turns, for which nine cases were averaged, and Figure 5 presents the results for sharply curved turns, for which seven cases were averaged.

Relationships Between Measured Spectra and Vehicle Dynamics

Figures 3, 4, and 5 show that the body-acceleration response spectra are generally multipeaked. This is expected because of the nature of the steering and suspension systems and the guideway inputs. The guideway inputs excite the vehicle through the front and rear wheel sets. The sidewall inputs act to steer the vehicle, both front and rear. The general nature of guideway roughness would be expected to follow that of highway roughness and, because of the time delay between inputs acting at the front and rear of the vehicle,

Figure 3. Ensemble-averaged spectral densities and one-third-octave band values—full speed along the back straight: (a) vertical acceleration, (b) transverse acceleration, and (c) longitudinal acceleration.



kinematic resonances (3) in the body heave, pitch, yaw, roll, and transverse motions are anticipated at frequencies of

$$f = kV/W \qquad (k = 1, 2, 3, \ldots) \tag{5}$$

where V = vehicle speed and W = wheel base.

For the AIRTRANS vehicle, W = 5.5 m (18 ft) between guide wheels and 4.3 m (14 ft) between drive wheels; at the full speed of 7.6 m/s (25 ft/s), peaks are expected at intervals of about 1.4 Hz in the lateral acceleration and 1.78 Hz in the vertical. These kinematic resonances are apparent in the experimental results.

In some frequency ranges, these kinematic resonances coincide with the vehicle dynamic modes. The primary vertical modes derived on the basis of mass and stiffness data obtained from the vehicle manufacturer are given below (1 kg = 2.2 lb and 1 kg/m = 0.0560 lb/in).

Figure 4. Ensemble-averaged spectra and one-third-octave band values—full speed around 242-m (800-ft) radius turn: (a) vertical acceleration, (b) transverse acceleration, and (c) longitudinal acceleration.

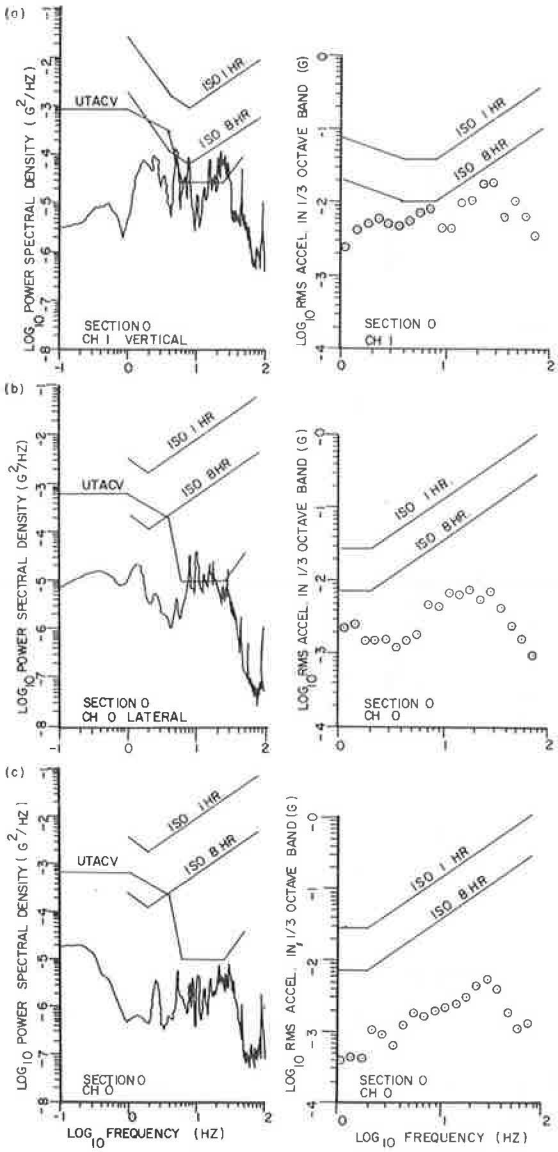
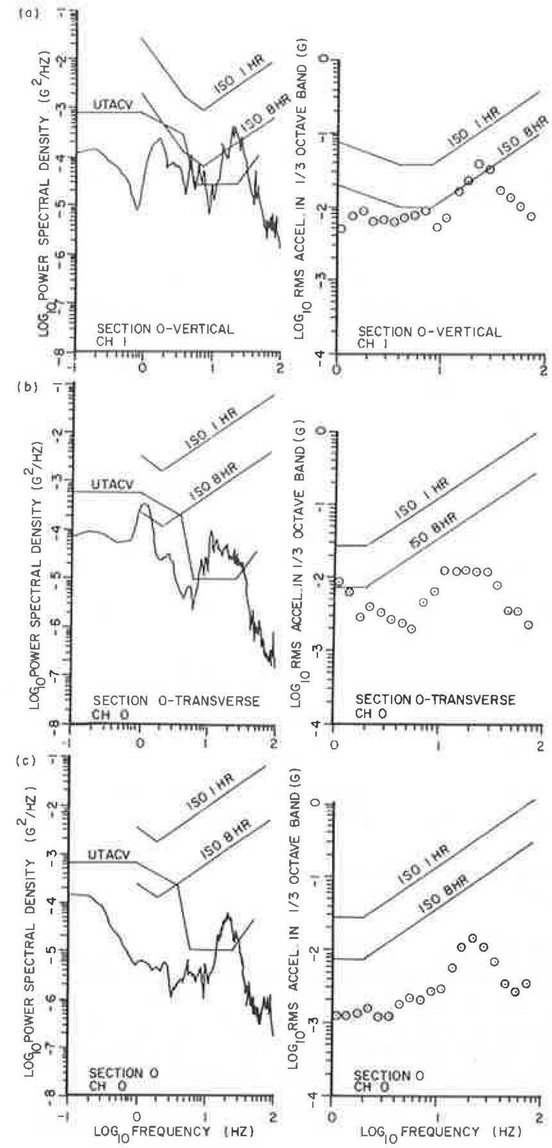


Figure 5. Ensemble-averaged spectra and one-third-octave band values—full speed around 46-m (150-ft) radius turn: (a) vertical acceleration, (b) transverse acceleration, and (c) longitudinal acceleration.



Parameter	Value
Sprung mass, kg	3960
Load with 10 passengers, kg	772
Unsprung masses (each axle), kg	1250
Air-bag springs (total), kg/m	3144
Tire stiffness (total), kg/m	328 000
Body-bounce frequency, Hz	1.25
Wheel-hop frequency, Hz	6.0

Figure 3a shows that the body-bounce mode at 1.25 Hz does not stand out strongly, but that there is a general peak in the acceleration response at about 2 Hz that arises because of the proximity of the bounce mode to the fundamental vertical kinematic resonance. Other peaks at approximately 3.5 Hz and 5.0 Hz are identified. The 5.0-Hz peak is heightened because of its proximity to the natural frequency of the wheel-hop mode. The peaks in the spectrum at 30 and 60 Hz are caused by excitation from the on-board air-compressors required to run the air-bag secondary suspension.

Turning to the transverse response case, in a mathematical model described by Healey (6), the prime transverse body mode occurs near 1.5 Hz and the lateral guidebar bounce mode occurs around 4 Hz. Figure 3b shows peaks at the 1.5-Hz primary natural frequency and multiple resonances at intervals close to the 1.4-Hz interval predicted for the lateral steering kinematic resonances. Further comparison between four-degree-of-freedom lateral models and the data in Figure 3b is given by Smith and others (6).

Figure 4 shows that there is little difference between travel on large-radius turns and along straight sections. Apparently, little steering action is taking place. Data given by Murray (7), which consider the measurement of guideway sidewall roughness, showed that in these areas, only light steering motions occur.

Comparison between Figures 3 and 5 shows that the action of positive steering around the sharp turns increases the vertical-acceleration levels, particularly in the 20 to 25-Hz range, and also the low-frequency transverse-acceleration levels. The increase in low-frequency transverse content comes from long-wavelength irregularities in the sidewall profile.

Probability Distributions

Figure 6 shows that the probability of exceeding a given level of vertical acceleration within a 10-s record is very close to the Gaussian normal. This may be expected. In these records, there are only small amounts of low-frequency acceleration and, in a selection of 4096 data points, many samples of higher frequency. For data with significant linear trends, such as for guideway roughness measurement, this happy result may not be true.

If each 10-s record is assigned its rms acceleration values, then it is possible to calculate the probability of experiencing a ride of less than, for example, 0.05*g* by extracting the percentage of 10-s sections having rms accelerations less than 0.05. Over the total ride around the loop, approximately 120 such sections were found; their corresponding cumulative probability functions were calculated.

Figures 7 and 8 show the cumulative probability for exceeding the rms acceleration taken over the whole test loop where the 10-s interval was taken as the time for calculation of the rms accelerations. Here, the Gaussian distribution function is not followed; the nature and design of the test loop has contributed some sections of sharply curved turns on which higher acceleration levels are inevitable and many sections with levels close to average. There are also some sections having low rms accelerations. Many of these occur in sections where the vehicle speed is slow because of system control command.

Ride Quality and Comfort Levels

The question of relating data on ride motion to anticipated comfort levels for passengers has been a perplexing one for many years. Early work dealt with the evaluation of simple harmonic motions, but the AIRTRANS motions are of a broad-band random nature. It has been suggested (5) that such ride motions be evaluated from the point of view of passenger safety in terms of a one-third-octave band analysis and compared with reduced comfort limits for various exposure times. Such comparisons give rise to the one-third-octave band results as given in Figures 3, 4, and 5. This approach is insufficient, however, because the degree of acceptability of a ride meeting the 1-h exposure guide, but not the 8-h exposure guide, is not given. As a general observation, the 1-h exposure reduced-comfort guideline (5) would allow far larger vertical accelerations than were found in AIRTRANS.

A more appropriate approach has recently been suggested by Jacobson, Kaulthau, and Richards (8). After many correlation studies working with small aircraft (and more recently buses, as discussed in a paper in this Record), they suggest comfort equations that link the combined axial accelerations to a comfort level and finally to the percentage of satisfied passengers. Their comfort equation (8), given for the case in which transverse accelerations are greater than 62 percent of the vertical, is

$$C = 2 + a_{vert} + 25a_{trans} \quad (2 < C < 5) \tag{6}$$

where

a_{vert} = rms vertical acceleration;
a_{trans} = rms transverse acceleration; and

Figure 6. Probability density and cumulative probability distributions for a typical section.

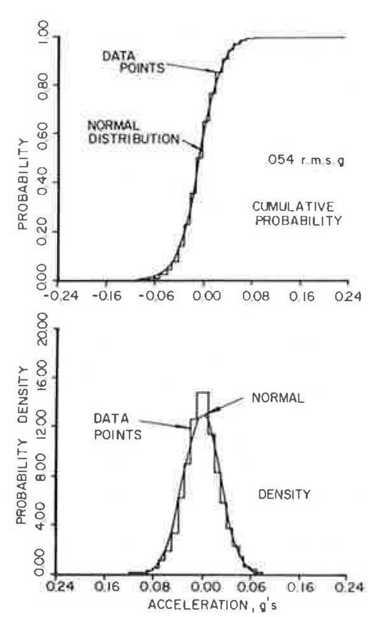


Figure 7. Cumulative probability for exceeding transverse acceleration taken over the complete test loop.

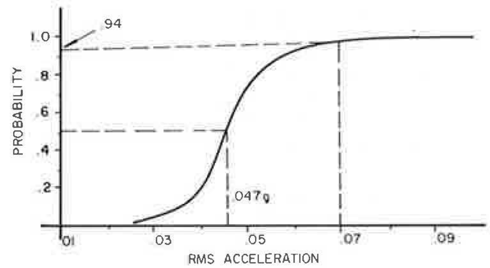
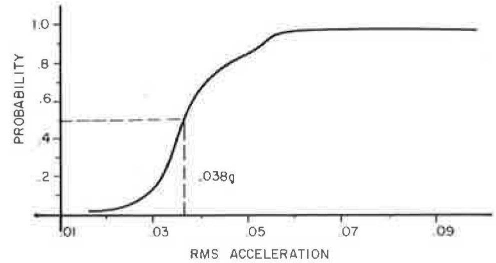


Figure 8. Cumulative probability for exceeding vertical acceleration taken over the complete test loop.



C = 2 (comfortable), 3 (neutral), 4 (uncomfortable), or 5 (very uncomfortable).

At the 70 percent passenger satisfaction level, C = 3.4 (8).

Because AIRTRANS passengers face the side of the vehicle, the transverse direction for passenger comfort is the longitudinal vehicle direction. However, in most of the sections examined, the rms longitudinal acceleration was the smaller of the horizontal plane motions (Figures 3b and 3c) and, by following identical procedures for evaluating horizontal plane motions (5), it seems appropriate to use the vertical and transverse accelerations in computing a comfort-level number.

Finally, under the assumption that the AIRTRANS transverse and vertical accelerations are always correlated and that a_{trans} is related to a_{vert} by

$$a_{trans} = 0.8a_{vert} \quad (7)$$

(which has been found to be the case over many individual sections analyzed), it follows that

$$C = 2 + 21a_{vert} \quad (8)$$

and for a 70 percent satisfaction level, $a_{vert} \cong 0.07\ g$. Figure 7 shows that this level of satisfaction is expected over 94 percent of the network loop.

A previous study (9) of rides in automobiles showed that the vertical acceleration correlated strongly with the ride rating; ratings for 80-km/h (50-mph) travel over a U.S. highway in an American sedan were between three and four (9). The corresponding vertical-acceleration-level band was between 0.035 and 0.055 g. The AIRTRANS rms vertical-acceleration levels average 0.047 g, which is within the bound of the automobile comfort.

CONCLUSIONS

It would appear that the ride quality of the AIRTRANS vehicle, as measured in terms of the vertical and transverse components of body acceleration, will yield a 70 percent satisfaction level 94 percent of the time. This conclusion is based on the assumption of a comfort equation developed for small aircraft that may not be precisely applicable. However, it is also supported by a favorable comparison of the vertical-acceleration levels with those measured in an American sedan traveling at 80 km/h (50 mph) over a U.S. highway.

The probability distribution of the acceleration level within a 10-s section of record is closely modeled by a Gaussian distribution. The spectra as measured at the floor of an AIRTRANS vehicle show that vertical, transverse, and longitudinal accelerations are multipeaked with the major peaks in the 1.0 to 6.0-Hz range. These peaks can be explained in terms of the primary vehicle resonances and the kinematic resonances induced by the delays between the guideway inputs at the front and rear of the vehicle.

ACKNOWLEDGMENTS

I wish to acknowledge the financial support of the University Research Program, U.S. Department of Transportation. The support of the Langley Research Center, National Aeronautics and Space Administration, and the Transportation Systems Center, U.S. Department of Transportation, for equipment loans, and the cooperation of the engineering staff of the Dallas-Fort Worth Airport Board are gratefully recognized.

REFERENCES

1. Symposium on Ride Quality. Proc., National Aeronautics and Space Administration, Technical Memorandum X-3295; U.S. Department of Transportation, Rept. DOT-TSC-OST-75-40, Nov. 1975.
2. J. J. Catherines, S. A. Clevenson, and H. F. Scholl. A Method for the Measurement and Analysis of Ride Vibrations of Transport Systems. National Aeronautics and Space Administration, TND-6785, May 1972.
3. A. J. Healey, E. Nathman, and C. C. Smith. An Analytical and Experimental Study of Automobile Dynamics With Random Roadway Inputs. Trans., ASME, Journal of Dynamic Systems, Measurement, and Control, Vol. 99, No. 4, Dec. 1977, pp. 284-292.
4. A. J. Healey. Digital Processing of Measured Vibration Data for Automobile Ride Evaluation. In Passenger Vibration in Transportation Vehicles, ASME, Special Publ. No. AMD, Vol. 24, 1977, pp. 1-18.
5. Guide for the Evaluation of Human Exposure to Whole-Body Vibration. International Organization for Standardization, 2631, 1972; ANSI, New York.
6. C. C. Smith, S. Tsao, and A. J. Healey. Lateral Steering Model for AIRTRANS. University Research Program, U.S. Department of Transportation, June 1976.
7. W. R. Murray. Guideway Sidewall Roughness for the Dallas-Fort Worth AIRTRANS. Univ. of Texas, Austin, MS thesis, 1976.
8. I. D. Jacobson, A. R. Kuhlthau, and L. G. Richards. Application of Ride-Quality Technology to Predict Ride Satisfaction for Commuter-Type Aircraft. Proc., Ride-Quality Symposium, National Aeronautics and Space Administration, Technical Memorandum X-3295; U.S. Department of Transportation, Rept. DOT-TSC-OST-75-40, Nov. 1975, pp. 45-65.
9. A. J. Healey, R. K. Young, and C. C. Smith. Automobile Ride-Quality Experiments Correlated to ISO-Weighted Criteria. Proc., Ride-Quality Symposium, National Aeronautics and Space Administration, Technical Memorandum X-3295; U.S. Department of Transportation, Rept. DOT-TSC-OST-75-40, Nov. 1975, pp. 581-601.

Effects of Deceleration and Rate of Deceleration on Live Seated Human Subjects

C. N. Abernethy, G. R. Plank, and E. D. Sussman, Transportation Systems Center, U.S. Department of Transportation
H. H. Jacobs, Dunlap and Associates

This paper describes the testing of seated human subjects to determine the maximum deceleration and associated rate of change of deceleration (jerk) at which the majority of potential users of automated-guideway-transportation systems will remain securely in their seats. The subjects

underwent various levels of deceleration and associated jerk in an instrumented vehicle while seated normally (forward facing); sideways (turned 90° counterclockwise from the direction of travel); and normally, but tilted backward (facing forward, but with the entire seat tilted 5° backward). The subjects also underwent various levels of jerk (seated normally only). Two groups of subjects were chosen to represent the anthropometric extremes of potential passengers: males larger than 95 percent of the male population and females smaller than all but 5 percent of the female population. Estimates based on these tests of the maximum permissible emergency deceleration are 0.47 *g* for forward-facing, seated passengers and 0.41 *g* for side-facing, seated passengers. Tilting the entire seat assembly back 5° increased the estimated maximum permissible deceleration to 0.52 *g*.

A major problem in the design of transit systems is the selection of the levels of deceleration and the associated rate of change of deceleration (jerk) used for emergency and service stops. These levels have an important effect on the headway (the time or distance maintained between vehicles) and, therefore, on the passenger-flow rate of the system. Shorter headways allow higher flow rates, but require greater decelerations and jerks. However, increasing the deceleration level increases the probability of injury to the passengers caused by dislodging them from their seats. This potential for injury becomes an even greater problem in conservatively designed systems because false-alarm stops will outnumber true emergencies. These false-alarm stops increase passenger exposure to excessive deceleration levels and, thereby, degrade safety.

The problem, therefore, is to determine the deceleration and jerk levels that will maximize the passenger-flow rate of the system while minimizing injuries to the passengers caused by decelerations.

BACKGROUND

There has been very little experimental research on this topic, and of this limited research, only two previous studies have used live human subjects. In a study directed at developing specifications for street railways (trolley cars), Hirshfield (1) accelerated standing subjects at constant jerk rates of between 1 and 10 *g*/s. The participating subjects were 11 to 78 years old, weighed 39 to 107 kg (87 to 235 lb), and were 132 to 193 cm (4 ft 4 in to 6 ft 4 in) tall. In this study, the foot movement accompanying loss of balance resulted in the opening of a sensor switch. Loss of balance occurred at 0.16 *g* for both forward-facing, unsupported males wearing low-heeled shoes and forward-facing, unsupported females wearing high heels. Loss of balance occurred at 0.23 *g* for subjects holding an overhead strap and at 0.27 *g* for subjects holding a vertical stanchion.

The second study [Browning (2)] also measured only standees. Ninety subjects ranging from 15 to 65 years old participated. The subjects could face either forward or backward and use a handhold if they so desired. Observer ratings of movement indicated that the subjects reacted equally to acceleration (facing forward) or deceleration (facing backward). Ratings of slight relative movement occurred at 0.055 *g* for unsupported subjects, at 0.115 *g* for subjects holding the hand rail, and at 0.18 *g* for fit adults holding the hand rail. Safe emergency decelerations in excess of 0.2 *g* were postulated for seated subjects.

A more recent study (3) performed with seated anthropometric dummies used static test procedures. A 79.4-kg (175-lb) cloth-covered buttock form was pulled from a standard transit seat, and a spring scale was used to measure the force. Forces equivalent to 0.94 *g* acting on the buttock form were required to dislodge it from a forward-facing, contoured seat covered with barley-cloth vinyl. For the same seat facing sideways, forces equivalent to 0.97 *g* were required to dislodge the form. No attempt to validate these figures through dynamic testing was reported.

In an analytical study, Fox and Dryden (4), using a biomechanical computer model, found that 0.559 *g* would be required to dislodge a forward-facing 95th percentile [98.4 kg (215 lb), 186.2 cm (6 ft 1 in)] male model from its seat.

None of these investigations studied seated human subjects. However, some automated-guideway-transit (AGT) systems are projected to achieve high passenger-flow rates by using many small vehicles that have all passengers seated and short headways. Consequently, the design of these systems requires knowledge of the effects of deceleration and jerk on seated passengers to ensure that they are simultaneously safe and efficient. None of these studies provides such data.

APPROACH

This study was designed to determine the deceleration levels required to dislodge potential passengers under typical conditions. These typical seating, passenger, and stopping conditions suggested the following choice of independent variables: seat orientation, seat tilt, level of jerk, and subject size. The relations among subject size, age, and sex were not considered.

Under each set of conditions, large and small human subjects were subjected to controlled decelerations while seated in a standard transit seat. Switches placed in the seat pan indicated when the subject was dislodged from the seat.

The study was conducted in three segments or tests that were designed to determine the effects of seat orientation, seat tilt, and level of jerk on passenger dislodgment. The two seat orientations selected (forward facing and side facing) are those most commonly installed in transit systems. The seat tilt angle selected is the greatest degree of tilt possible commensurate with comfort and ease of egress. The jerk levels were chosen to represent an operational level and an emergency level. The methodology and results of these tests are described in the next two sections. The most sensitive dependent variable was found to be the level of deceleration at which the subjects left the seat pan.

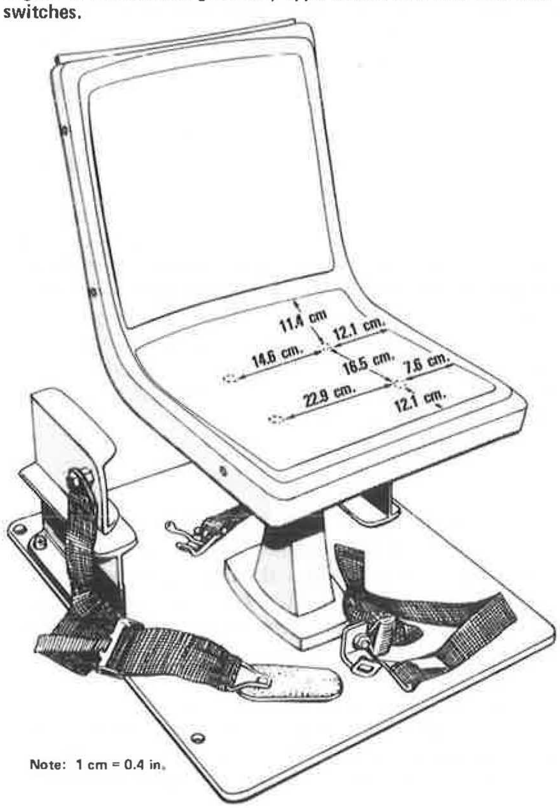
METHOD

Subjects

Twenty subjects were recruited by newspaper advertisement from the general population of Ayer, Massachusetts. Ten of the subjects were females below the 10th percentile of weight and height for females [i.e., less than 46.7 kg (103 lb) in weight and 155 cm (61 in) in height] and 10 were males above the 90th percentile of weight and height for males [i.e., more than 85.7 kg (189 lb) in weight and 183 cm (72 in) in height] (5). A summary of subject characteristics is given below (1 kg = 2.2 lb and 1 cm = 0.4 in).

Characteristic	Small Females (N = 10)	Large Males (N = 10)
Age, years		
Mean	23.6	35.4
Range	18 to 32	25 to 50
Weight, kg		
Mean	44.0	99.1
Range	41.5 to 46.7	85.7 to 113
Height, cm		
Mean	152	188
Range	147 to 158	180 to 196

Figure 1. Automated-guideway type transit seat with installed switches.



Before participating in the tests, the subjects were required to pass a medical examination administered at the Fort Devens Hospital. They also completed an informed-consent form.

Apparatus

A commercially available seat was selected to be representative of the modern transit seat to be used in AGT systems. For these tests, it was mounted in the rear section of a large van. Switches were installed at the front and rear of the seat bottom so as to open when a subject was dislodged (Figure 1). A force-balance accelerometer mounted on the vehicle floor next to the transit seat was used to measure the deceleration of the vehicle, and a fifth wheel measured the vehicle velocity. The decelerations were initiated by the driver through the standard braking system of the vehicle. The driver controlled the deceleration level by monitoring a U-tube accelerometer attached to the front windshield. The following analog data were recorded on a 14-channel magnetic tape recorder: velocity, switch openings, and actual decelerations.

Each subject was fitted with a pair of denim trousers to eliminate frictional differences caused by clothing design and material. A five-point racing-type safety harness was loosely fastened about the subject and adjusted to allow him or her to slide to the front edge of the seat, but no further. All subjects were fitted with motorcycle helmets to prevent accidental head injuries.

Procedure

Ten of the subjects recruited for the tests were used in the studies designed to evaluate the effect of seat orientation, and the remaining 10 were used in the studies designed to evaluate the effect of seat tilt. From the total group of 20, 6 subjects were later drawn to participate in the studies designed to evaluate the effect of jerk. Within each experiment, the effect of passenger size was evaluated by selecting half the subjects to be 10th and lower percentile females and half to be 90th and higher percentile males.

The tests were conducted in clear weather on a straight, dry macadam road at Fort Devens in Ayer, Massachusetts. Up to 4 subjects/d were tested with up to 10 decelerations per subject, 5 for each experimental condition in the first two tests and 3 each for the third test. Each subject was briefed on the entire procedure before the testing. They were asked to sit as they would normally sit in a transit vehicle such as a bus, remain relaxed, and not anticipate the decelerations. The five-point safety harness was fastened and adjusted. The subject, when seated, could see through the front windshield of the passenger's side of the vehicle, but was prevented from viewing the driver's activities by a curtain. Each subject was tested individually; the other subjects were able to view the tests from a distance.

In each test, the driver would accelerate the vehicle to 64 km/h (40 mph) and then brake it at a constant deceleration until it stopped. Each subject experienced 10 predetermined deceleration levels.

The experimental conditions for the effects of the independent variables (passenger size, seat position, seat tilt, and jerk) on the dependent variable (deceleration at which the subjects were unseated) are summarized below:

1. Ten subjects (5 large and 5 small) were exposed to 10 decelerations at high jerk. For 5 of the decelerations, the subjects were seated facing forward in a normally mounted seat. For the other 5, they were seated facing sideways.
2. A second set of subjects (5 large and 5 small) were exposed to 10 decelerations each at high jerk. For 5 of these decelerations, the subjects were seated facing forward in a normally mounted transit seat. For the other 5, they were seated tilted 5° back.
3. Six of the previous subjects (3 large and 3 small) were exposed to 6 decelerations seated facing forward in a normally mounted seat. The onset of 3 of these decelerations was rapid (high level of jerk), and the onset of the other 3 decelerations was gradual (low level of jerk).

Design of Tests

All three tests were designed to be analyzed by using two-way, fixed-effects analyses of variance with repeated measures on the second factor. The first factor in all three analyses was subject size (S) (small versus large). The second factor was the experimental condition: seat orientation (O) in the first test, seat tilt (A) in the second, and jerk level (J) in the third. To ensure that any obtained significant differences in the repeated variable were interpretable as due to the variable tested and not to procedural or subject differences, the order of presentation of treatments was arranged according to the following three constraints:

1. Subjects were not to experience either the forward or reverse order of any two adjacent deceleration levels (to reduce subject anticipation),
2. Both subject groups were to experience the same order of treatment in each experimental condition (to allow proper comparison of their responses), and
3. The deceleration levels used in each experimental condition (up to five in some cases) were to be counterbalanced over the five subjects within each group.

Because it was disruptive and time-consuming to change the seat position or tilt after each run, all five decelerations for one seat arrangement were presented sequentially.

RESULTS

Analysis

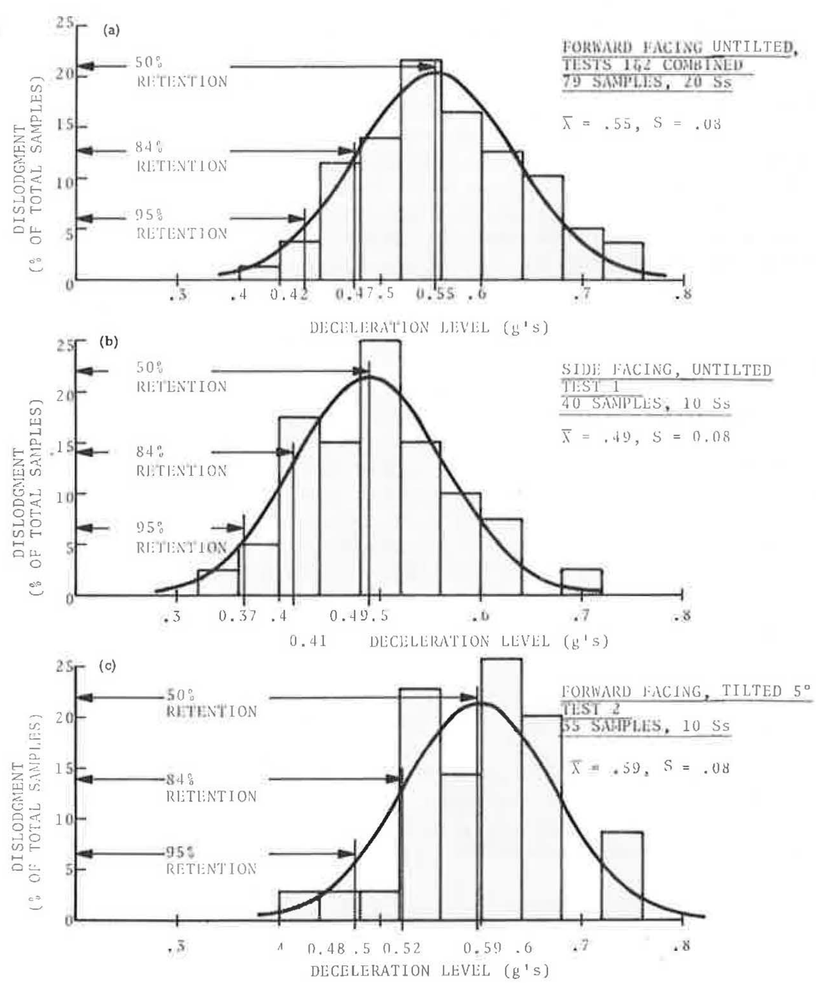
Examination of the data showed that the left rear switch provided a common and sensitive measure of subject displacement in all phases of the experiment, and therefore only the data for this switch were used in the analysis. The dependent variable reported and analyzed is the actual deceleration at the time of the opening of the switch, for all trials in which the switch opened. Because the subjects were exposed to predetermined decelerations, rather than to deceleration until the switch opened, there were cases in which the switch did not open, and no value of deceleration that caused dislodgement was obtained. This occurred only at the lowest deceleration levels (0.3 *g* in test 1 and 0.4 *g* in tests 2 and 3) and was a problem only with the small subjects. Because of the failure to obtain reliable and consistent measures at these low deceleration levels, the data were considered anomalous and excluded from the analysis.

To determine whether there was any difference in the deceleration level at which the passenger seat switch opened under the control conditions (forward facing and untilted), a t-test was used to compare the data taken under these conditions for tests 1 and 2. No significant difference was identified ($t = 0.14$, degrees of freedom = 77), indicating that the slight differences associated with subject or order variables can be attributed to chance.

Because there was no statistically significant difference, the data from the control conditions were pooled. Tests for skewness and kurtosis were performed on the 20 forward-facing, untilted subjects of tests 1 and 2. The results of these two tests indicate that the data were distributed normally, which permits the use of statistical parametric techniques. Figure 2a represents these pooled data.

To estimate a conservative level of deceleration that would allow the great majority of passengers to remain securely in their seats, the standard deviation was computed and subtracted from the mean. This value represents the deceleration level at which 84 percent of the occupants would remain securely in their seats. In a similar manner, a second estimate obtained by subtracting two standard deviations represents the deceleration level at which 95 percent of the occupants would remain securely in their seats. The deceleration levels at which 50, 84, and 95 percent of the subjects will remain securely in their seats are indicated in Figure 2a for the control condition. Similarly, Figure 2b represents the data obtained when the seat was oriented to the side, and Figure 2c represents the data obtained when it was tilted back 5°. (The small number of these data points precluded vigorous tests for normality.) A discussion of these tests follows.

Figure 2. Comparison of distributions of observed data with the normal (results of tests 1 and 2).



Test 1: Seat Orientation

Five large and five small subjects seated in the standard transit seat, facing forward or facing sideward toward the driver's side, were decelerated at levels of up to 0.3, 0.4, 0.5, 0.6, and 0.7.

As anticipated, the subjects seated facing forward sustained higher decelerations without dislodgment than did those facing sideways. The mean deceleration (±1 standard deviation) required to displace the subjects from the seat was 0.55 (±0.08) *g* in the forward position and 0.49 (±0.08) *g* in the side position for the same subjects. The analysis of variance shown below indicates that this difference had a probability of less than 0.001 of being due to random variation rather than to seat orientation (Ss = number of subjects).

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F	P
Between subjects					
S	1	0.000 82	0.000 82	0.034 92	NS
S x Ss	8	0.018 77	0.002 35	–	–
Within subjects					
O	1	0.021 00	0.021 00	26.948 88	0.001
O x S	1	0.000 30	0.000 30	0.390 46	NS
O x Ss	8	0.006 23	0.000 78	–	–
Total	19	0.047 12	–	–	–

There was no difference due to subject size or the interaction of subject size with seat orientation.

Observations made during the deceleration tests indicate that, generally, for subjects in the forward-facing seat position, the higher decelerations resulted in the torso pitching forward and rotating about the hips, followed by the buttocks sliding forward in the seat until the entire body reached the maximum excursion allowed by the restraint system. The reaction to lower decelerations was primarily rotational with little sliding.

In the side-facing seat position, the reaction to all deceleration levels was a rotation of the upper torso about the right buttock. At higher deceleration levels, this rotation resulted in the maximum excursion allowed by the restraint system. The pure rotation was, in all likelihood, due to the deep contour of the seat in the side position.

Test 2: Seat Tilt

It was anticipated that tilting the entire transit seat back 5° from the standard mounting position would permit subjects to sustain higher decelerations without dislodgment than they could with the seat in the standard position. The 5° tilt was chosen as a compromise between increased retention and comfort. Five large and five small subjects seated facing forward in the standard transit seat, normally mounted (i.e., untilted) or tilted 5° back, were decelerated at levels of up to 0.4, 0.5, 0.6, 0.7, and 0.8 *g*.

The mean deceleration (±1 standard deviation) required to displace the subjects from the seat as measured by the opening of the left rear switch was 0.56 (±0.08) *g* in the normally mounted position and 0.59 (±0.08) *g* in the tilted (5°) backward position for the same subjects. The analysis of variance shown below indicates that this difference has a probability of less than 0.04 of being due to random variation rather than to seat tilt.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F	P
Between subjects					
S	1	0.005 02	0.005 02	1.677 15	NS
S x Ss	8	0.023 97	0.003 00	–	–
Within subjects					
A	1	0.011 38	0.011 38	5.806 31	0.041
A x S	1	0.001 75	0.001 75	0.892 37	NS
A x Ss	8	0.015 67	–	–	–
Total	19	0.057 79	–	–	–

There was no evidence of a difference due to subject size or the interaction of subject size with seat tilt.

Observations made during the deceleration tests indicated that, for subjects in the forward-facing seat position, for both tilt angles, the reaction to the higher deceleration levels was as follows: The upper torso pitched forward and rotated about the hips, and this was followed by the buttocks sliding forward in the seat. The reaction to lower deceleration levels was a rotation with less violent sliding.

Test 3: Jerk

Three large and three small subjects were selected for this test from those participating in the previous two tests. These subjects were exposed to decelerations applied with high (1.5 to 2.0 g/s) or low (0.1 to 0.5 g/s) levels of jerk. The deceleration levels were up to 0.4, 0.5, and 0.6 *g*. All subjects were exposed to all six combinations of jerk and deceleration while seated facing forward in a standard transit seat mounted in the normal position.

The mean deceleration (±1 standard deviation) required to displace the subjects from the seat was 0.45 (±0.11) *g* for the low levels of jerk and 0.49 (±0.09) *g* for the high levels of jerk. The analysis of variance shown below indicates that there are no significant differences due to the high and low levels of jerk, the two subject sizes, or the interaction of subject size with level of jerk.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F	P
Between subjects					
S	1	0.017 40	0.017 40	1.178 03	NS
S x Ss	4	0.059 10	0.014 77	–	–
Within subjects					
J	1	0.004 45	0.004 45	2.772 86	NS
J x S	1	0.001 90	0.001 90	1.184 84	NS
J x Ss	4	0.006 41	0.001 60	–	–
Total	11	0.089 26	–	–	–

Observations made during these tests indicated that, in most cases, the higher level of jerk induced a torso rotation that was followed by sliding of the buttocks on the seat, and the result of the lower jerk was primarily sliding, with little rotation of the torso.

DISCUSSION OF RESULTS

The goals of this study were to provide data to help understand the influences of various parameters on seated passengers during emergency stops and to obtain estimates of the emergency decelerations to be specified for transit systems.

These data indicate that seated passengers can safely experience deceleration levels about twice those reported for standees (1, 2). A conservative estimate of the emergency deceleration to be specified in the design of transit systems on which 84 percent of the occupants of an untilted forward-facing standard transit seat will remain securely within their seats is 0.47 g. To ensure retention of 84 percent of the occupants at a side-facing seat, the best estimate is 0.41 g; for the occupants of a facing-forward seat tilted back 5°, the best estimate is 0.52 g.

Consequently, these data support the use of forward-facing, back-tilted seating to permit high decelerations with a low incidence of passenger dislodgment. (Obviously, backward-facing seating permits higher decelerations; however, many AGT systems operate bidirectionally, and many users prefer facing the direction of movement.)

The small observed differences in the data obtained under different rates of change of deceleration are not attributable to treatment effects, nor are the small differences observed between the two different sizes of subjects.

The results of this study should be applied cautiously; no attempt was made to distinguish independently among the effects, if any, of subject age, sex, and size. Although no significant effects of jerk were found, further studies of jerk should not be precluded because only six subjects participated and only a limited, poorly controlled range of jerk levels was possible in this study.

ACKNOWLEDGMENTS

This report is based on research supported by the Transportation Systems Center, U.S. Department of Transportation and sponsored by the New System and Automation Division, Urban Mass Transportation Administration.

REFERENCES

1. G. F. Hirshfield. Disturbing Effects of Horizontal Acceleration. Electric Railway Presidents' Conference Committee, Bulletin No. 3, Sept. 1932.
2. A. C. Browning. Human-Engineering Studies of High-Speed Pedestrian Conveyors. Royal Aircraft Establishment, Technical Rept. No. 71104, Oct. 1972.
3. Forward and Side Loads to Unseat Passengers: Comparison of Flat Seat With Contoured Seat. American Seating Co., March 14, 1975.
4. J. N. Fox and R. D. Dryden. Biomechanical Modeling of Transit Passengers Subjected to Accelerative Forces. Public Transportation Center, Univ. of Texas, Arlington, August 31, 1975.
5. A. Damoud, H. W. Stroudt, and R. A. McFarland. The Human Body in Equipment Design. Harvard Univ. Press, 1966.

Passenger Perceptions of the Helicopter: Ride-Quality Considerations

Michael B. Schoultz,* IBM Federal Systems Division, Owego, New York
William J. Snyder, Langley Research Center, National Aeronautics and Space Administration, Hampton, Virginia

A summary of the National Aeronautics and Space Administration civil helicopter ride-quality research is presented. Three components of the ride-quality problem are discussed: passenger preconditioning; in-flight cabin conditions, such as noise and motion; and flight duration. Passenger anxiety and motivation for flying were studied as potentially important factors influencing perceptions of ride quality. In addition, the relation between these factors and previous flight experience is examined. The relative importance of cabin noise and vibration is determined for a range of noise and vibration combinations, and changes in passenger comfort due to ride improvements are evaluated. The importance of flight duration on ride satisfaction is discussed.

In the highly competitive field of public transportation, consideration of the needs of the user is essential. Accordingly, to make the helicopter a feasible transportation alternative, one must, among other things, understand how to design the system to be attractive to potential users. It is important to identify the relations between the attributes of the helicopter and the passenger's evaluation of the effects of these attributes as they relate to his or her satisfaction. One source of this information is passenger evaluation based on actual experience of these attributes.

One of the more important attributes of a transportation system, and especially of the helicopter, is the ride environment. The multiharmonic nature of helicopter vibration presents a special problem in evaluating subjective responses to this environment. Previous studies of subjective evaluation of this type of environment have shown that the levels of each of the component rotor harmonics can be well within acceptable limits and still combine to produce an unacceptable ride (1). An equally important part of the helicopter environment is the noise level. Thus far, there have been few investigations of the interactive effects of different combinations of noise and vibration on a passenger's satisfaction with the ride. Therefore, it is important to extend ride-quality research into these areas and to identify and evaluate passenger responses to the helicopter environment. Also requiring attention are the modifying effects of other ride-quality variables, such as flight duration, low-frequency motion, temperature, and visual cues, as well as such passenger psychological variables as anxiety, attitude toward flying, and flight experience.

The passenger-acceptance flight-research phase of the National Aeronautics and Space Administration (NASA) Civil Helicopter Technology Program is designed to investigate all of these variables through controlled experiments that use a large transport helicopter configured to commercial-type specifications. The experiments are designed to simulate real-world conditions as closely as possible. This paper discusses the objectives and results of the first phase of the program. An overview of other flight research activities of the program can be found elsewhere (2).

OBJECTIVES

The primary objective of the passenger-acceptance flight tests is to evaluate the ride environment of the helicopter. Figure 1 illustrates the three components of the ride-quality problem that were studied: (a) factors affecting a passenger's preconditioning, (b) cabin-environment conditions, and (c) flight duration. Previous studies (3, 4) have shown that all of these components are important in determining a passenger's evaluation of his or her environment and, therefore, his or her satisfaction with the ride.

The helicopter as an alternative mode of transportation is a relatively new concept to most travelers; few have actually experienced this kind of travel. Therefore, preconditioning may be an especially important factor in determining a passenger's satisfaction. Three preconditioning factors appear particularly important: attitude toward flying, previous experience with air travel and with helicopter flight, and anxiety about and motivation for flying.

A second component of the ride-quality problem is the cabin environment and how it is perceived by the passenger. Motion, noise, temperature, and visual cues all contribute to this environment. In this part of the research, the object is to identify the relative importance of each of these factors and to determine the improvements that could best increase passenger satisfaction.

A previous investigation (5) of the helicopter ride environment showed passengers to be reasonably well satisfied on flights of 10 to 15-min duration; however, no data are available on longer flights. Therefore, a final object of this program is to evaluate how the duration of exposure to the helicopter environment affects ride satisfaction.

Figure 1. Components of ride-quality problem.

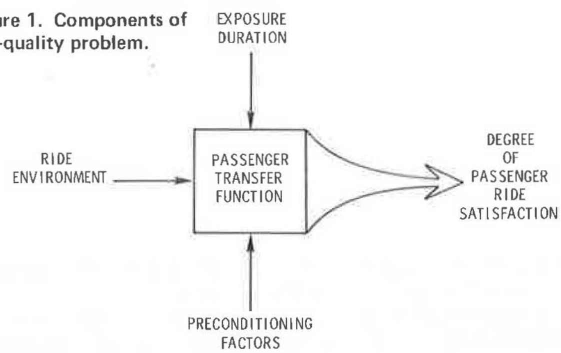


Figure 2. CH-53 civil helicopter research aircraft.

TEST VEHICLE

The civil helicopter research aircraft (CHRA) is a reconfigured CH-53A military transport helicopter (Figure 2), modified from its baseline configuration by the addition of higher rated engines and transmissions. Its other systems are unchanged. Its basic characteristics are given below (1 kg = 2.2 lb, 1 km/h = 0.62 mph, 1 m = 3.3 ft); a more complete description may be found elsewhere (6).

Characteristic	Value	Characteristic	Value
Gross mass, kg	16 586	Width (blades folded), m	4.7
Cruise speed, km/h	278	Diameter of main rotor, m	21.9
Length, m	17.2		
Height, m	5.1		

This aircraft, which is approximately 17 m (56 ft) long, can carry up to 44 passengers in its commercial configuration. At a cruising speed of 77.2 m/s (150 knots), its range is approximately 400 km (250 miles). It represents a vehicle that has the potential to be used in intraurban as well as short-haul intercity transportation.

The NASA CHRA has been modified to a partial representation of a commercial aircraft by the installation of a 4.1-m (13.3-ft) airline cabin containing four rows of four abreast seating. The seats are mounted on tracks with an adjustable seat pitch from 76 to 94 cm (30 to 37 in) in 2.5-cm (1-in) increments. The individual sections of each double seat are separated by an armrest and have individually adjustable backrests. The seating characteristics are shown in comparison with those of other short-haul aircraft in Table 1 (5).

The passenger cabin is separated from the remainder of the vehicle in the fore and aft directions by bulkheads that are vibration isolated from the airframe, acoustically treated, and paneled on the passenger side by a cork covering. A plywood floor furnished with carpet padding and a high-pile carpet has been installed to cover the metal floor of the aircraft. The inside of the fuselage panels is treated with damping tape, and both the panels and stringers are covered with bagged fiberglass. The ceiling is equipped with two layers of vinyl separated with foam. The interior trim panels are mounted on vibration isolators and give the interior the appearance of a conventional commercial aircraft. [A more thorough description of the acoustical treatment of the cabin and its effectiveness in reducing interior noise levels is given by Howlett and Clevenson (7).]

Because of the prohibitive cost and difficulty of conversion, the cabin is equipped with only four windows, two on each side of the aircraft, adjacent to the first and third rows of seats. The windows are approximately 38 by 38 cm (15 by 15 in) in size and of double-pane con-

Table 1. Short-haul aircraft seat dimensions.

Aircraft	Width (cm)	Depth (cm)	Armrest	Leg Room (cm)	Adjustment	Type of Cushion
Twin Otter	24	46	No	24	None	Foam
Nord 262	37	44	Yes	20	None	Foam
Beech 99	44	44	No	20	None	Foam
S-61 Helicopter	48	46	Yes	22 to 27	None	Foam
CHRA	38	46	Yes	38	Yes	Foam

Note: 1 cm = 0.4 in.

struction, with the inner pane attached to the acoustical treatment, lightly tinted, and provided with an opaque shade. The temperature in the cabin is maintained by heating and air-conditioning systems, and individually adjustable air vents for recirculated air are provided for each passenger.

DESIGN AND PROCEDURE OF EXPERIMENT

Figure 3 shows the variables studied and the degree of control of these variables during the flight experiments. In this phase, eight flights were conducted, each with a complement of 15 passengers. Two groups of passengers were selected from among both NASA and non-NASA applicants. Each group represented equivalent mixes and numbers of four types of passenger, reflecting previous flight experience and attitude toward flying: (a) never flown before, (b) like flying and some flight experience, (c) no strong feeling about flying and some flight experience, and (d) like flying and a frequent air traveler (defined as at least 6 flights/year on the average). None of the subjects had previously flown in a helicopter. The seating arrangements were controlled to ensure that each type of passenger was represented throughout the cabin.

Each group of passengers flew four flights, one at each of four durations: 25, 50, 75, and 100 min. The order of flight-duration presentation was different for each group, and passengers flew only 1 flight/d and never on consecutive days. The total series of flights took place within a 15-d period. Because of scheduling conflicts, some passenger substitution was required; 13 substitutes were used during the eight flights.

Passenger evaluations were taken by questionnaires during and after each flight. Each flight consisted of a number of 10-min test segments, as shown below.

Flight Duration (min)	Test Segments per Flight	Flight Duration (min)	Test Segments per Flight
25	2	75	4
50	3	100	5

The segments were equally spaced over the duration of the flight. Each was divided into four 1.5-min evaluation periods during which a prescribed combination of noise and vibration was presented.

As Figure 3 illustrates, neither noise nor motion is precisely controllable. However, certain helicopter airspeeds were found to result in highest and lowest vibration levels in the cabin. Similarly, by opening and closing the rear door to the passenger cabin, the interior noise level could be varied between a high and a low condition. Typical ranges of these noise and vibration levels are shown below; more details of the characteristics of this environment are given by Snyder (2) and Snyder and Schlegel (6).

Factor	High	Low
Motion, g_{rms}		
a_z (vertical)	0.13 to 0.17	0.10 to 0.12
a_y (lateral)	0.08 to 0.11	0.05 to 0.07
Noise, dB(A)	88 to 92	83 to 85

The four combinations of noise and vibration were presented randomly during each test segment. At the end of each period, the passengers were given 20 s to record their evaluations of the comfort and the ride by using a seven-point comfort scale on which one represented very comfortable and seven represented very uncomfortable (3, 4, 10). In addition, they were asked to identify which factor(s) they found most objectionable (including no factors objectionable). These evaluations were designed to identify changes in ride quality as a function of exposure duration and to study the relative importance of cabin noise and vibration. Noise, motion, and temperature data were recorded to correlate the subjective responses with the environmental conditions.

A passenger's apprehension and motivation were evaluated by the Spielberger State-Trait Anxiety Inventory (8), a two-part questionnaire designed to measure (a) the usual or typical level of anxiety (trait anxiety) and (b) the present level of anxiety (state of anxiety). The trait-anxiety questionnaire was administered to the passengers several weeks before the flights began, and the state-anxiety questionnaire was administered just before takeoff, after the helicopter rotor had been engaged.

Finally, the passengers were given a brief postflight questionnaire in the briefing room at the end of each flight. On these questionnaires, they were to evaluate their overall reaction to the flight, indicate which factors contributed the most to their evaluation, and identify the system improvements they felt could best be made.

DISCUSSION OF RESULTS

Preconditioning Factors

Many preconditioning factors have the potential to influence a passenger's perception of his or her transportation mode; these include preconceptions based on the opinions of others, previous experience on the mode, previous experience on similar systems, and personal likes and dislikes. Figure 4 illustrates the influence of a passenger's previous flight experience on his or her perception of the helicopter ride quality: The more experienced air traveler tends to be more critical and demanding. Almost twice as many of this type of passenger as compared to passengers with less flight experience are not satisfied with the helicopter as a means of transportation. Similarly, experienced passengers are less tolerant of the noise during the flight. There appear to be two reasons to explain the influence of flight experience on perceptions of ride quality. First, the experienced air traveler has flown more on other air vehicles and, hence, has an increased tendency to base his or her evaluation on those flights. Because the vibration and noise levels of the helicopter are higher than those of the typical jet transport, it can be expected to rate lower on this comparison. Second, anxiety and motivation for flying seem to be underlying causes of this tendency. Whereas a small amount of anxiety increases alertness, an increase in the amount of anxiety eventually leads to a narrowing of one's focus of attention (9). It also appears that a high level of motivation tends to narrow one's focus of attention. As shown in Figure 5, the passengers who are either highly apprehensive or highly motivated (eager) are more apt to be satisfied with the ride environment of the helicopter. That is, they are less apt to notice the noise, vibration, and other negative aspects. The table below indicates that frequent air travelers tend to be less motivated and apprehensive about flying; almost twice as large a percentage of frequent air travelers are neither highly motivated nor highly apprehensive as compared to passengers with less flight experience.

Previous Flight Experience	Anxiety and Motivation Level (percentage of row total) Highly Motivated	Highly Apprehensive	Neither
Never flown previously	33	58	9
Some previous flight experience	36	41	23
Frequent air traveler	15	44	41

Figure 3. Experimental control of variables to be studied.

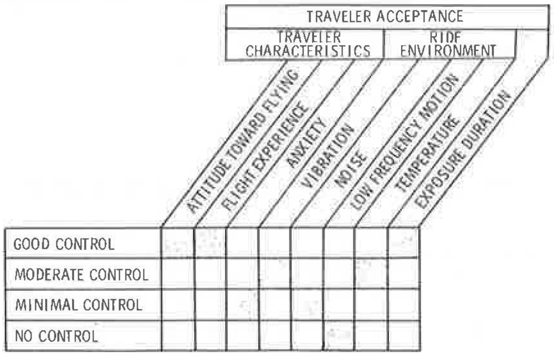


Figure 4. Importance to ride satisfaction of (a) previous flight experience and (b) noise.

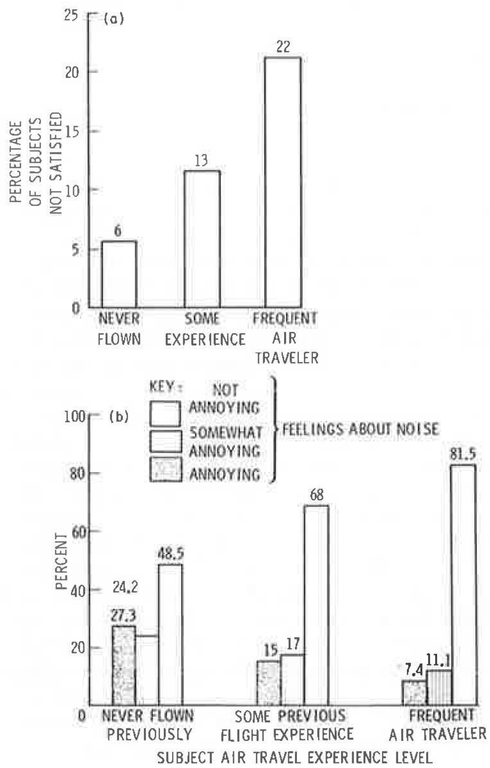


Figure 5. Importance to passenger satisfaction of anxiety and motivation.

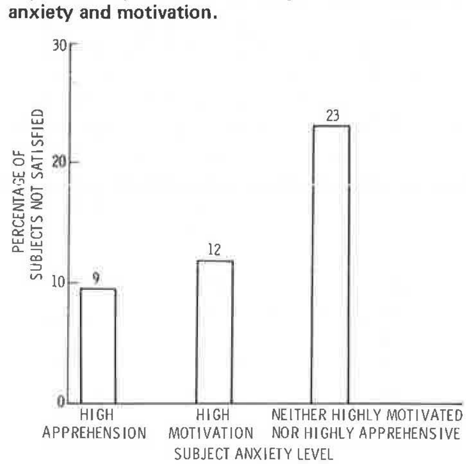


Table 2. Rank ordering of physical factors contributing to passenger comfort.

Factor	Total Sample	Previous Flight Experience: Never Flown	Some Experience	Frequent Air Traveler
Noise	1	4[a]	1	1
Ability to see out of window	2	1[a]	2	2
Vibration	3	5[a]	2	3
Seat comfort	4	2[a]	4	8[a]
General motion	5	6	6	4
Temperature	6	3[a]	7	5
Pressure change	7	7	8	6
Sudden jolts	8	9	9	7
Seating space	9	8	5[a]	9

[a]Significant differences in rankings.

From this, one can hypothesize that as travelers adapt to travel on the helicopter, their motivation for flying and their apprehension will decrease, which will increase the tendency to rate the ride and the vehicle less acceptable.

Environmental Factors

As part of the postflight questionnaire, the passengers were asked to rate the factors contributing the most to their comfort evaluation. Nine factors were listed and space was provided for additions. The mean ranking of the nine factors is shown in Table 2. The interior noise level is the factor most significant in the passenger's dissatisfaction with the ride, and visual cues and vibration levels are also ranked high. The ability to have a good view is a particularly important asset. Because it typically operates at lower altitudes than conventional fixed-wing aircraft, the helicopter presents a view to which the passenger can more easily relate. However, the value of cabin windows is somewhat diminished by the strobe effect caused by light passing through the main rotor disc. This phenomenon is known as rotor flicker, and 20 percent of the passengers found it distracting. Several commented that the flicker seemed to add to the sensation of vibration. This table also shows the rank order of the factors contributing to the comfort evaluation for various subgroups of the total sample and that passengers who had never flown previously ranked the factors significantly different than did those passengers with previous flight experience. Seat comfort and temperature are more important to those passengers who had no previous flight experience, and noise and vibration are less important. The results given in this table support the hypothesis that anxiety and motivation are important factors influencing a passenger's perception of his or her ride quality; the majority (91 percent) of the passenger group with no previous flight experience is either highly motivated or highly apprehensive about flying.

Figure 6 illustrates the relative importance of cabin noise and motion as contributors to ride discomfort: 69 percent of the passengers find the noise either somewhat annoying or annoying, and 26 percent find the motion to be somewhat annoying or annoying. The impacts of reductions in noise and vibration levels on passenger satisfaction are shown in Figure 7. There are two significant factors among the environmental conditions of the CHRA. First, even at the lowest levels achievable, noise is considered the most objectionable factor by a majority of the passengers. Second, while vibration is also an important factor, priority should be given to reducing the cabin noise to achieve the greatest reduction

Figure 6. Passenger feelings about noise and motion.

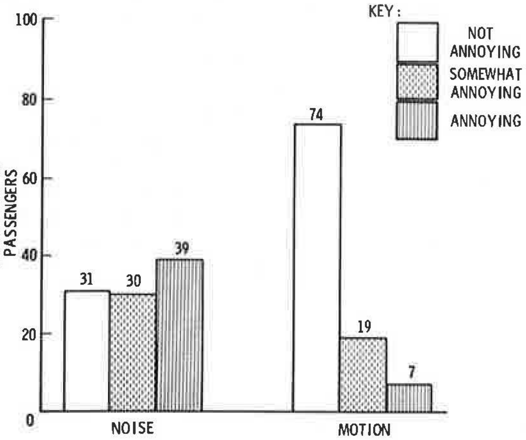
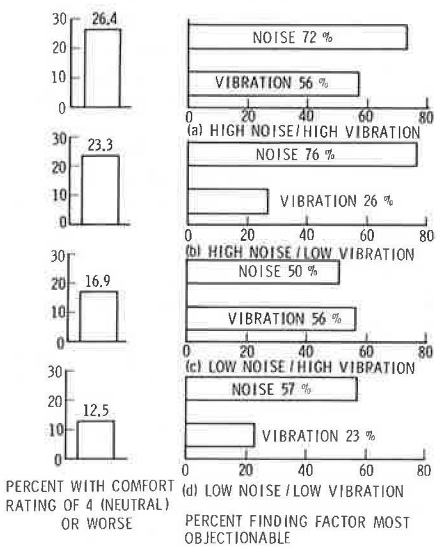


Figure 7. Importance of noise and vibration reductions.



in the number of passengers with a comfort rating of neutral or worse.

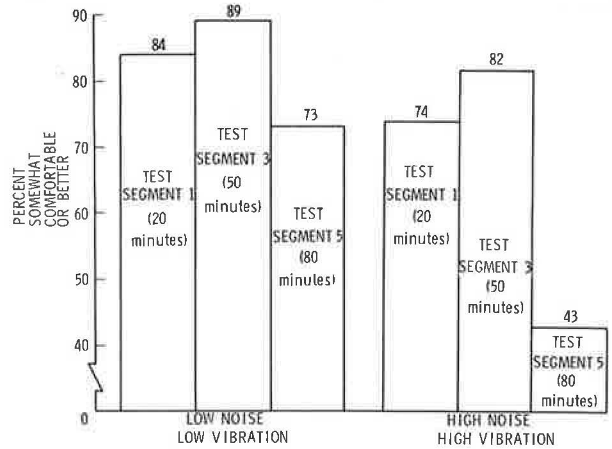
The impact of noise and motion on in-flight activities, such as reading, writing, talking, and sleeping, is indicated in the table below.

	Performance Difficulty (percentage of row total)		
Activity	Not Difficult	Somewhat Difficult	Very Difficult
Reading	72	21	7
Writing	45	50	5
Talking	40	45	15
Sleeping	40	26	34

Talking and sleeping are the most affected activities; 60 percent of the passengers find these activities either somewhat or very difficult.

Finally, because passengers in the second and fourth rows of seats lack windows, one must consider the influence of a lack of visual cues on passenger ride evaluation. The table below shows the percentages of passengers in each row with neutral or lower comfort; finding the noise and motion somewhat annoying, annoying, or very annoying; and having some doubts about another flight.

Figure 8. Influence to ride comfort of flight duration.



Seat Row	Neutral or Lower Comfort	Finding Noise Annoying	Finding Motion Annoying	Doubts About Another Flight
1	21	79	58	8
2	6	78	63	13
3	6	88	38	9
4	32	88	68	24

Persons in the fourth row are obviously less satisfied with the ride than are those in other rows. However, this could be due to either the increased noise in the rear of the cabin (particularly at the pure-tone frequency of the helicopter main transmission) or to the lack of windows or both. Further investigation of the importance of visual cues by comparing the responses of passengers in row two with those in rows one and three showed no apparent trends. It appears that the presence of visual cues is more of a positive contribution to passenger satisfaction than is the absence of visual cues a detriment.

Flight Duration

Another factor that is important in a passenger's ride satisfaction is the duration of exposure. Before the research flights, it was anticipated that with the noise and vibration levels shown above, there would be some point in time at which the previously comfortable environment would begin to be uncomfortable. Figure 8 shows the percentage of passengers somewhat comfortable or better for the low-noise and low-vibration and high-noise and high-vibration environments as a function of the length of the test segment. There is a noticeable reduction in comfort for the fifth test segment in both environments. This segment was presented approximately 75 to 80 min after takeoff. The results shown in Figure 9 reinforce this conclusion. Here, passenger evaluation obtained after the flight indicates greater dissatisfaction with the longer flights than with the shorter ones. Clearly, if this vehicle is to be used for short-haul intercity transportation where flight durations of 1 to 2 h are necessary, improvements in the interior noise and vibration are particularly important.

Willingness to Fly Again

It is hypothesized that a passenger's willingness to take another flight depends on, among other variables, how comfortable he or she was on the flight just experienced (10). Therefore, as part of the postflight evaluation, passengers were asked to indicate their willingness to

Figure 9. Influence of flight duration on willingness to fly again.

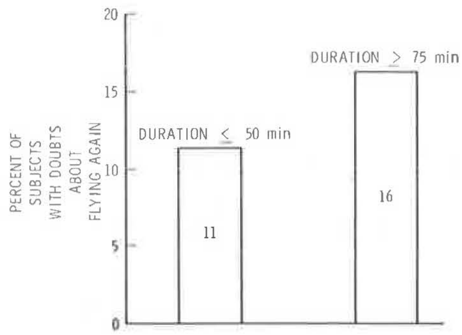
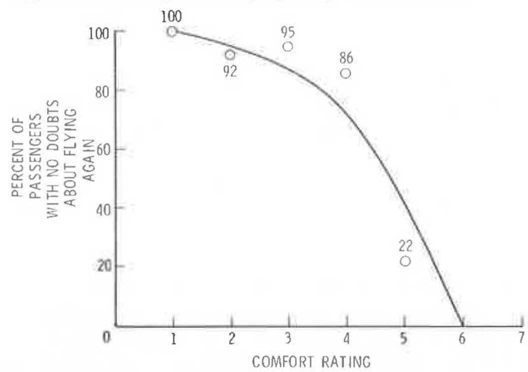


Figure 10. Willingness to fly again by comfort level.



fly again in light of the flight they had just experienced. The table below shows that the hypothesis appears to be valid; there is a strong relation between a passenger's comfort rating for this trip and his or her willingness to fly again.

	Willingness to Fly Again (percentage of row total)			
Comfort Rating	Eager	No Doubt	Some Doubt	Prefer Not
Very comfortable	100	0	0	0
Comfortable	53	39	5	3
Somewhat comfortable	27	68	5	0
Neutral	43	43	0	14
Somewhat uncomfortable	0	22	78	0
Uncomfortable	0	0	100	0
Very uncomfortable	0	0	0	100

The chi-square value for this table is highly significant, and the contingency coefficient is 0.65. The usefulness of this relation is shown in Figure 10 in which the eager-to-fly-again and have-no-doubts categories have been combined and plotted against the passenger's overall comfort rating. This can be considered as a percentage-satisfied curve. From this information, one can estimate the percentage of passengers willing to fly again from their comfort rating. The conclusion is obvious: If the goal is to achieve 90 percent of the passengers with no doubts about flying again, then one must provide a flight that yields a comfort rating of three or more.

SUMMARY

Three components of the ride-quality problem have been examined: passenger preconditioning, in-flight cabin conditions, and flight duration. The results indicate that passengers who are frequent air travelers are generally neither highly apprehensive nor highly motivated toward flying. These passengers, typically business travelers, are more critical of their flight environment and are more difficult to satisfy. Noise is the most significant factor in a passenger's dissatisfaction with his or her ride environment, and a reduction in noise has the greatest impact in decreasing the percentage of passengers finding the ride uncomfortable. Flight duration increased beyond 70 min resulted in a decrease in passenger comfort and overall system acceptance.

REFERENCES

1. R. Gabel, B. O. Henderson, and D. A. Reed. Pilot and Passenger Vibration Environment Sensitivity. Journal of American Helicopter Society, Vol. 16, No. 3, July 1971, pp. 39-43.
2. W. J. Snyder and M. B. Schoultz. Civil Helicopter Flight Research. American Institute of Aeronautics and Astronautics, Paper 76-896, Sept. 1976.
3. A. R. Kuhlthau and I. D. Jacobson. Investigation of Traveler Acceptance Factors in Short-Haul Air-Carrier Operations. National Aeronautics and Space Administration, Technical Memorandum X-2620, Oct. 1972, pp. 211-228.
4. I. D. Jacobson and A. R. Kuhlthau. STOL Ride-Quality Criteria: Passenger Acceptance. American Institute of Aeronautics and Astronautics, Paper 72-790, Aug. 1972.
5. D. Noskowitz and I. D. Jacobson. Passenger Demographics and Subjective Response to Commuter Aircraft in the Northeast. Short-Haul Air Transportation Program, Department of Engineering Science and Systems, Univ. of Virginia, Charlottesville, Memorandum Rept. 403219, Dec. 1974.
6. W. J. Snyder and R. G. Schlegel. Vehicle for Civil Helicopter Ride-Quality Research. Proc., National Aeronautics and Space Administration, Technical Memorandum X-3295, Nov. 1975, pp. 97-116.
7. J. T. Howlett and S. A. Clevenson. A Study of Helicopter Interior-Noise Reduction. National Aeronautics and Space Administration, Technical Memorandum X-72655, May 1975.
8. C. D. Spielberger, R. L. Gorsuch, and R. E. Lushene. STAI Manual for the State-Trait Anxiety Inventory. Consulting Psychologists Press, 1970.
9. M. Hamilton. Diagnosis and Rating of Anxiety. In Studies of Anxiety, Paper read at the World Psychiatric Association Symposium on Aspects of Anxiety, London, Nov. 1967 (M. H. Lader and M. Harold, eds.), World Psychiatric Association and Royal Medical-Psychological Association; Headley Brothers, London, 1967, pp. 76-79.
10. L. G. Richards and I. D. Jacobson. Ride-Quality Evaluation: Questionnaire Studies of Airline Passenger Comfort. Ergonomics, Vol. 18, No. 2, 1975, pp. 129-150.

Dr. Schoultz was at the University of Virginia, Charlottesville, when this research was performed.